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FOREIGN TECHNOLOGY DIVISION

CORROSION-MECHANICAL WEAR OF EQUIPMENT

by

B. B. Kruman and V. A. Krupitsyna

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* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

Corrosion-mechanical wear of equipment. B. B. Kruman and V. A. Krupitsyna, Moscow, "Machine Building," 1968, 104 pp.

The book gives an account of problems of the wear of constructional steel with friction in corrosive fluids and mainly in neutral salt solutions.

The mechanism of mutual corrosion-mechanical wear of plain carbon steel and the effect of different factors on the intensity of this process are described.

Results are given of laboratory and industrial experiments, which allow estimating the effectiveness of different means of decreasing the wear of steel articles with friction in solutions of neutral salts.

The book is intended for engineering and technical workers of the chemical and petroleum industries; it can be useful for people engaged in the investigation of problems of corrosion-mechanical wear of metals.

There are 48 figures, 11 tables, 49 bibliography references.

Reviewer: Candidate of Technical Sciences Ye. M. Zayetskiy.

INTRODUCTION

Owing to the swift development of different directions of the chemical industry, number of mechanisms, units of friction of which operate directly in corrosion-active liquid media is continuously increased - solutions of acids, alkalis and neutral salts.

In the petroleum industry with the mechanized extraction of oil, the number of cases of the destruction of metal-consuming and expensive sections of equipment under the joint effect of friction and electrochemical corrosion continuously increases. Thus, for instance, at the Baku fields one of the central problems of depth-pump exploitation of oil wells is the intense wear of elevator pipes, which occurs in the mineralized stratified water.

The presence of an active medium on metallic rubbing surfaces conditions the appearance of the specific form of their destruction, which is called chemical-mechanical wear.

By the chemical-mechanical wear of metals and alloys we mean the destruction of metallic rubbing surfaces under the action of two simultaneously occurring processes: chemical (or electrochemical) interaction of the metal with the environment and mechanical destruction of products of this interaction.

If according to the definition of Yu. Evans we examine corrosion as a process of the destruction of metal or alloy as a result of the

chemical (electrochemical) reaction or physical dissolution [46], it follows to consider that elements of chemical-mechanical wear should be observed in processes of the abrasion of machine parts operating in a very wide range of conditions of operation. It is clear that these elements will not always be predominate over other processes simultaneously occurring on surfaces of friction and will not always determine the character and regularities of the process of wear as a whole. They can be the leading factor only when wear is inflicted not on the metal or alloy themselves, but the oxide film or other adsorptive-chemical compound, which is continuously formed on rubbing surfaces under the effect of the environment.

Proceeding from the mechanism of corrosional phenomena with which friction can be linked, it follows to consider separately two varieties of the process of chemical-mechanical wear of metals:

a) with occurrence of it in conditions of chemical interaction of the metal with the environment, i.e., with friction in the gaseous medium or in the presence of liquids of nonelectrolytes;

b) with the occurrence of it in conditions of the electrochemical interaction of metal with the environment, i.e., with friction in the presence of liquids of electrolytes: solutions of acids, alkalis and neutral salts.

Expediency of a separate examination of these two varieties of the process of chemical-mechanical wear will be determined not only by the difference in their mechanisms and regularities, but also by the fact that the effect of oxidation of rubbing surfaces on the magnitude of wear in a gaseous medium or in the presence of liquid of nonelectrolytes is in contrast to the effect rendered by electrochemical corrosion.

Numerous investigations have established that with oxidizing wear in the region of dry and boundary friction losses are considerably less than losses observed with other forms of wear.

Very characteristic in this respect are results of experiments of I. G. Nosovskiy, who studied the development of different forms of wear of steel 45 with friction in a medium containing oxidizing and nonoxidizing gases. With dry friction in a gaseous medium containing 99.7% oxygen, the magnitude of wear was minimal in the whole speed range of slip applied usually in laboratory experiments. This range was reduced with friction in an air medium and in carbon dioxide. With dry sliding friction in a medium of inert gases (nitrogen, argon) the intensity of wear exceeded tens of times the intensity observed with friction in a medium of oxidizing gases. The author explains the obtained results by the fact that in a medium of oxidizing gases not the metal itself but products of its oxidation wore out: the products of wear were different iron oxides. With friction in a medium of inert gases "grasping" of surfaces was observed, and products of wear were particles of metal of various dimensions [28].

A similar opinion is declared also by V. A. Kislik, who considers that in usual conditions of the operation of rubbing parts, i.e., in units operating at normal external temperature in an air medium and in the range of pressures and speeds of movement usually encountered in practice, the least rate of wear corresponds to fatigue breakdown of unevennesses of surfaces and the destruction of oxidized films [16].

Absolutely different results are obtained with the joint action of friction and electrochemical corrosion.

One and the earliest investigations of the process of chemical-mechanical wear of steel with friction in corrosive liquid media, carried out by N. D. Tomashov and V. G. Sapozhnikova in connection with a search for means of extending the period of service of shafts on ships, showed that electrochemical corrosion, conditional by the constant access of sufficiently strong electrolytes (solutions of chlorides, sea water), considerably accelerates the destruction of rubbing surfaces. In this case the continuous destruction of products

of electrochemical corrosion conditions the high speed of interaction of the metal with the environment [36]. Approximately at the same time A. G. Samartsev and his colleagues noted the decisive influence of electrochemical corrosion on the rate of grinding of metals. The supply to grindable surfaces of a more active electrolyte considerably increases the rate of treatment [32]. The investigations of W. Hillis and W. Mackenzie showed that owing to the water phase of the wood, which is a complicated buffer system of acetic acid and its salts with pH equal 2.6-3.0, considerable intensification of the wear of the woodworking tool occurs [48]. According to many authors, the sharp reduction in the service period of railroad rails in tunnels as compared to the longevity of them on open sections of the track is caused by the joint effect of friction in electrochemical corrosion [13, 47, 49].

A list of these examples could be continued. All of them leave no doubt of the fact that electrochemical corrosion, in contrast to oxidation with friction in a gaseous medium, considerably accelerates the process of wear of metallic surfaces.

In connection with what has been said one should stress one more circumstance, which is illustrated well in work [13]. Experiments were conducted with different carbon and alloyed rail steels, the hardness of which was changed by means of heat treatment. The check rail was of tire steel. The working medium was tap water, acidified by sulfiric acid up to pH = 4.18, which corresponds to an acidity of water drawings of products of corrosion of rails in tunnels. The specific pressure exceeded the pressure appearing in wheels of electric locomotives. In parallel with the determination of wear resistance of steels in the presence and absence of electrochemical corrosion, the rate of electrochemical corrosion in the absence of friction was also determined. From Table 1 one can see that independently of the brand of steel and form of heat treatment, material losses with the simultaneous action of electrochemical corrosion and friction are several times greater than losses observed with separate consecutive flow of these processes. The given

data will agree well with results of experiments of Ye. M. Zaretskiy, I. M. Katser and O. A. Petrova, who showed that in the process of the wear of steel 4Khl3 with friction in tap water corrosion and mechanical factors are commensurable, i.e., they play an approximately identical role [15].

Table 1. Data on the effect of corrosion on the intensity of wear of rail steels [13].

Brand of steel	HB	Losses of weight in $g/m^2 \cdot h$			Wear with joint action of friction and corrosion in $g/m^2 \cdot h$
		with friction and absence of corrosion	with corrosion without friction	total	
K-2	500 450 350	14,1 35,0 42,9	0,068 0,064 0,060	14,168 35,064 42,960	34,8 112,0 128,5
AO-1	500 450 350	21,6 37,2 50,0	0,071 0,080 0,072	21,671 37,280 50,072	86,0 112,0 170,0
TB-3	500 450 350	19,3 40,9 58,0	0,054 0,064 0,055	19,354 40,964 58,055	70,0 160,0 168,0
T-5	500 450 350	19,5 29,7 37,9	0,051 0,027 0,057	19,551 29,727 37,957	57,0 107,0 202,0
XB-2	500 450 350	29,3 34,6 42,5	0,078 0,079 0,073	29,378 34,679 42,573	81,9 87,3 233,0

There are bases to assume that the different effect of oxidation of rubbing surfaces in a gaseous medium and electrochemical corrosion on the magnitude of wear is conditioned by unequal states of surface layers of metal. With oxidizing wear in a gas medium plastic deformation of surface layers of the metal and an increase in the hardness of them are observed [18]. With friction in a corrosional-active liquid medium, plastic deformation and an increase in hardness of the surface layers are not revealed with the exception of cases when grasping of the surfaces occurs [5, 43].

In this work questions connected with the second of the indicated

varieties of the process of chemical-mechanical wear, called recently also corrosion-mechanical wear[1] are examined.

It is necessary to note that if the numerous investigations conducted, starting from 1928, in the region of chemical-mechanical wear in a gaseous medium permit at present judging with sufficient fullness the mechanism and regularities of this process, then the mechanism of wear of metals in corrosion-active liquids is the subject of a considerably smaller number of works. Results of these works, presented mainly in the form of articles placed in different journals and collections, deal with separate aspects of this question, are frequently contradictory and do not permit sufficiently clearly the presenting of concrete measures of combatting this form of destruction of rubbing surfaces in certain conditions of the operation of machine parts.

In examining works touching upon the joint effect of friction and corrosion, attracts attention the absence of a single view of the question about whether corrosion-mechanical wear is an independent form of destruction of rubbing surfaces. For clarity let us cite opinions of leading Soviet specialists in the field of friction and wear.

Basing the classification of forms of wear of machine parts proposed by him according to official criteria, M. M. Khrushchov notes that as a result of the combination of corrosion with various forms of mechanical effect, different forms of corrosional-mechanical wear can be obtained [42].

In another work, carried out jointly with M. A. Babichev, the same author indicates the possibility of a change in nature of the process of wear as a result of the effect of corrosion on the rubbing

[1]In the subsequent account the term corrosion-mechanical wear should be understood as wear with friction only in corrosion-active liquid media.

surface. Therefore, it is impossible to predict the behavior of any metal with a simultaneous effect on it of corrosion and friction according to data obtained during a separate study of the corrosion stability of this metal without friction or resistance to wear of it in the absence of corrosion. A metal, which corrosion-stable with respect to any corrosive medium due to the formation on it of a protective film, can appear absolutely unstable with friction in this medium provided the protective film does not appear by itself wear-resistant with respect to mechanical friction [43].

An absolutely different point of view is expressed by B. I. Kostetskiy. In the classification proposed by him of basic forms of wear of metals and alloys, the corrosion-mechanical wear is not considered as an independent form of destruction of rubbing surfaces. Inasmuch as phenomena of corrosion can occur both in mobile and motionless parts of machines, they are not directly connected with processes of friction and wear. Therefore, it is recommended to differentiate processes of wear in machines and corrosion phenomena in them. The absence of such delimitation additionally complicates the solution of theoretical and practical problems of the science of friction and wear of metals [18].

It is obvious that the question on the expediency of consideration of corrosion-mechanical wear as an independent form of destuction of metal rubbing surfaces represents not only a theoretical interest from the point of view of the classification of forms of wear of machine parts. The approach to this question and, first of all, the approach to the expediency of delimitation of mechanical and corrosion factors in the process of wear in many respects will be governed by the selection of specific methods of combatting destruction of rubbing surfaces occurring under the simultaneous effect of these factors.

This question is very complicated. There are, at least, two circumstances preventing a simple solution of it.

The first is the absence of formulas sufficiently reliably describing the joint effect of friction and corrosion in electrolytes.

It is known that the rate of formation of oxidized films on the surfaces of metal is determined by the magnitude of the change in free energy with transition of the metal into an ionic state. However, although there are data on the change in free energy of metals in reactions of oxidation [35], calculation of the real speeds of formation of oxide films is hampered by the fact that in real conditions the rate of the process of oxidation is not in a simple ratio, to the magnitude of the change in free energy. Certain authors consider the rate of formation of primary oxide films is so great that at room temperature it does not yield to investigation with the help of contemporary laboratory equipment [23]. If we add to this the absence of data on the real strength and resistance to wear of these films and other compound formed on rubbing surfaces under the effect of different corrosion liquid media, it becomes evident that the calculation of corrosion-mechanical wear of metals is as yet very difficult. Therefore, the process is investigated chiefly by experimental means.

The second circumstance is the absence of a sufficient quantity of laboratory experiments conducted by a single method and data of the observation of the character and regularities of corrosion-mechanical wear of machine parts in different conditions of operation. The latter conditions especially the empirical approach to the selection of means of extension of the service period of these parts. The creation of a single method combining the estimate of the magnitude of material losses with metallographic investigations of surface layers of the metal and study of the kinetics and dynamics of electrode processes occurring on rubbing surfaces would considerably accelerate the solution of many theoretical and practical questions, connected with the corrosion-mechanical wear of metals and alloys.

In this work, together with an attempt of an analysis and generalization of the source data on cor·osion-mechanical wear, results are given of experiments conducted by authors in laboratory and industrial conditions for studying the mechanism and regularities of wear of nonalloyed constructional steels with friction in solutions of neutral salts and an estimate of the effectiveness of different means of the decrease in intensity of this process.

Inasmuch as in the majority of practical cases of the corrosion of the steel in electrolytes chlorides are the basic corrosional agent, in the carrying out of laboratory experiments described in the work chiefly sea water was used, which is a solution of neutral salts, among which NaCl predominates. A large quantity of this salt is also dissolved in stratified water of petroleum deposits, which serve as a working medium in the carrying out of experiments with natural samples of equipment in operational conditions.

With the carrying out of the experiments the hypothesis was accepted on the possibility of the existence of a range of conditions within limits of which the intensity of wear is determined by corrosion processes occurring on surfaces of friction, and a range of conditions at which the predominant importance is factors of a mechanical nature. Results of laboratory investigations, which allowed estimating the effect of different factors of a corrosion and mechanical character of the intensity of the corrosion-mechanical wear of steel and also a comparison of these results with the given investigation of this process directly in industrial conditions confirmed the validity of this hypothesis.

A significant place in the work is given to the study of the corrosion-mechanical wear of steel with friction in deoxygenated solutions of neutral salts. The carrying out of these experiments permitted approximating conditions of laboratory experiments to conditions of the operation of certain sections of oil field equipment, the process of wear of which is described in the work. Furthermore, results of these experiments illustrate well the effect of a

strong corrosional agent, oxygen, on the intensity of the corrosion-mechanical wear of steel.

The investigaitons conducted allowed also estimating the effectiveness of different means of decreasing the corrosion-mechanical wear of steel units of friction in rigid operational conditions.

Not claiming to an exhausting elucidation of the question and realizing that prospects of the calculation of the intensity of the corrosion-mechanical wear of metals remain as yet barely reliable, the authors nevertheless trust that this work will be useful both for persons whose practical activity is connected with the operation of units of friction, operating in corrosion liquid media, and for persons engaged in investigations in this field.

CHAPTER 1

LABORATORY INVESTIGATIONS OF THE PROCESS OF MUTUAL WEAR OF CONSTRUCTIONAL STEEL WITH FRICTION IN SOLUTIONS OF NEUTRAL SALTS

1. Purpose and Methods of Laboratory Investigations

The laboratory investigations described in this chapter were conducted for the following purposes:

1) to study the mechanism of mutual wear of steel with friction in neutral salt solutions;

2) to investigate the effect of different factors of the mechanical nature on the intensity of corrosion-mechanical wear of steel; these factors were: means (duration) of friction, rate of slip, specific pressure, hardness, fullness of eliminating products of wear;

3) to investigate the dependence of mutual corrosion-mechanical wear of steel on factors determining the corrosion rate in solutions of neutral salts: access of oxygen to surfaces of friction, temperature of the medium, concentration of the solution, relationships of magnitudes of anodic and cathodic sections of the surfaces.

The experiments were conducted on a stand, the diagram of which is shown in Fig. 1.1. The housing and other parts of the working chamber of the stand, with the exception of the loading spring,

calibrated before the beginning of each experiment, were made of nonmetallic materials. The stand, together with the connecting rod-crank gear mechanism is fastened on a plate, united with the help of hinges with the base of the motor and reductor. By turning the plate about the hinges, it is possible to change the slope of the working chamber to a horizontal plane, and, consequently, the slope of samples to it by an angle the magnitude of which is 0° to 75°.

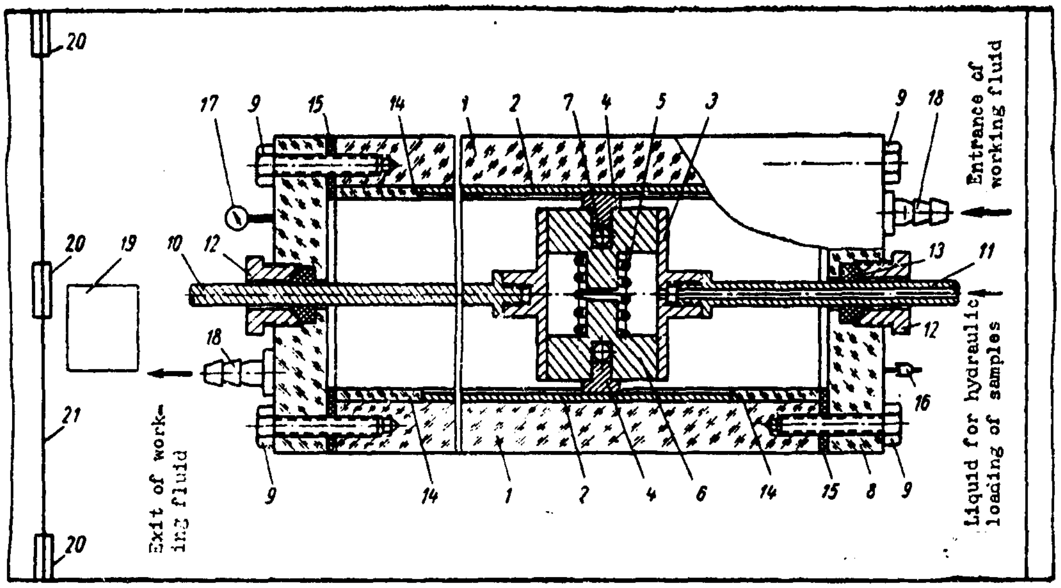


Fig. 1.1. Diagram of a stand for testing metals on corrosion-mechanical wear: with reciprocating motion: 1 - housing; 2 - fixed sample (guide); 3 - holder of mobile sample; 4 - mobile sample (slider); 5 - loading spring; 6 - casing of mobile sample; 7 - ball; 8 - cover; 9 - bolts; 10 - rod; 11 - hollow rod for hydraulic load of samples; 12 - cover stuffing box; 13 - stuffing box; 14 - plates for the installation of fixed sample; 15 - packing; 16 - contact thermometer; 17 - manometer; 18 - connecting pipe; 19 - connecting rod-crank gear mechanism; 20 - hinges; 21 - plate for installation of the electric motor.

The working fluid in carrying out the majority of experiments was sea (Caspian) water, which had the following chemical composition (in %): NaCl - 60.35; $MgCl_2$ - 5.18; $MgSO_4$ - 22.71; $CaSO_4$ - 8.88; $MgBr_2$ - 0.05; KCl - 1.23; $CaCO_3$ - 1.36; other salts - 0.24. In separate experiments the solution NaCl was used. The working fluid

had a constant temperature, maintained with the help of a hermetic thermostat. The liquid proceeded from the pressure system, was passed through a filter of resin KSG to remove the oxygen contained in it and entered the working cavity of the stand under a certain excess pressure adjustable by means of a valve.

The wear of the samples was determined by means of weighing on analytic scales, although it is known that the method of cut craters gives more exact results. However, the application of this method had to be rejected inasmuch as the edge of the crater can be a place of intense corrosion

2. Mechanism of Mutual Wear of Steel with Friction in Solutions of Neutral Salts

The practice of the exploitation of machine parts subjected to corrosion-mechanical wear indicates that together with conditions at which the action of mechanical factors prevails over the effect of corrosion processes occurring on rubbing surfaces there are conditions when factors stimulating corrosion determine the regularity and intensity of the wear.

Therefore, one of the most important problems, which inevitably appear in the very beginning of the study of the process of wear of any metal in a certain corrosion liquid medium, is the determination of conditions at which the action of corrosion or mechanical factor prevail.

Assumed as the basis of experiments carried out by authors to solve this problem in reference to the mutual wear steel with friction in solutions of neutral salts, were the following prerequisites.

Upon placing the steel sample into the solution of neutral salt, the surface of it corrodes. If part of this surface is continuously cleaned, the corrosion of it should be more intense as compared to the corrosion of the uncleaned part of the surface, on which the layer of the oxides carries out a protective function.

It is established that the potential of the steel subjected to continuous dressing, under a layer of neutral salt solution is displaced to the negative side of several hundreds of millivolts [17].

Thus, between the cleaned and uncleaned parts of the surface of the sample there should be a potential difference, which increases with an increase in the fullness of the dressing and increase in protective properties of the layer of oxides on the uncleaned part of the surface should form a macropair in which the cleaned part executes the function of an anode.

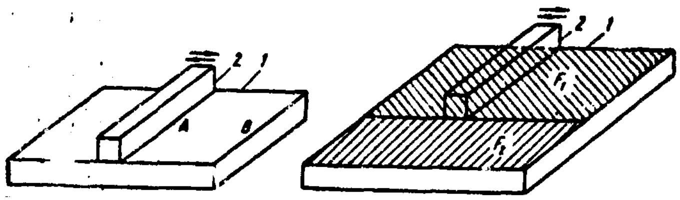
It is clear that the existence of this micropair does not exclude the possibility of the great influence of local microcells on the corrosion rate of both parts of the surface conditioned by its heterogeneity.

By works of G. V. Akimov and his colleagues it has been established that with electrochemical corrosion occurring with oxygen depolarization of the cathodes, the current intensity of the local element, which determines the material effect of corrosion, is directly proportional to the area of the cathode. The presence of such a dependence is confirmed also by works of other authors [2, 34].

Transferring this position to the mechanism of mutual corrosion-mechanical wear of steel in neutral salt solutions, it is possible to present the flow of this process according to the following scheme.

With the sliding of a short steel sample (subsequently, for brevity, called a slider) along a long sample (guide) manufactured from the same material, the surfaces of friction corrode, and products of corrosion are continuously destroyed and depart. If the width of the surface of friction of the guide is equal to the width of the surface of the slider (Fig. 2), the corrosion rate at each moment of time is determined by two factors: a) work of the

local microelements conditioned by the heterogeneity of rubbing surfaces; b) potential difference between the part of the surface of friction of the guide, outgoing at a given moment from the contact with the slider, and parts of the surface of friction of the sliding, which earlier made contact with it (for instance, between points A and B on Fig. 2a).



a) b)

Fig. 2. Diagram of an experiment for studying the effect of the magnitude of a nonrubbing part of the surface of the guide on the intensity of corrosion-mechanical wear of steel: 1 - guide; 2 - slider; F_1 - rubbing part of the surface of the guide· F_2 - nonrubbing part of the surface of the guide.

If the width of the surface of the guide is larger than the width of the surface of friction of the slider (Fig. 2b), added to the named two factors is a third - the potential difference between the rubbing and nonrubbing part of the surface of the guide. In this case, according to work [2], one should expect that the higher the ratio of areas of nonrubbing (F_2) to rubbing (F_1) parts of the surface of the guide, the more intense the corrosion of the rubbing part of the surface occurs.

It is obvious that if in the process of the mutual corrosion-mechanical wear of steel a considerable increase in intensity of wear will be observed with an increase in ratio F_2/F_1, the prevailing effect of the corrosion factor in this process should be considered indisputable.

The essence of experiments described below consisted in the determination of the region of prevalence of the corrosion factor over the mechanical factor in the process of mutual corrosion-mechanical wear of steel by means of studying the effect of ratio F_2/F_1 on the intensity of this process.

Samples were prepared from normalized steels 45. Surfaces of friction of the guide and slider, equal, respectively, to 210 × 10 and 10 × 10 mm^2, were ground, and the nonrubbing edges were insulated with bakelite varnish. Each friction pair was preliminarily worn for 10 h under a specific pressure of 3.3 kg/cm^2 and the speed of slip was 0.66 m/s. The rubbing and nonrubbing parts of the guide were prepared separately and were tightly pressed to each other on uninsulated lateral faces. The temperature of the working medium was 25°C, and the speed of the liquid in the cavity of the stand was $6 \cdot 10^{-5}$ m/s.

In all laboratory experiments carried out by the authors, with the exception of especially stipulated cases, the material, dimensions, initial cleanness of the rubbing surfaces, horizontal location of the samples in space, conditions of running-in of pairs of friction, method of insulation of the nonrubbing margins, temperatures of the working medium and speed of the medium in the working cavity of the stand were the same as they were in this experiment.

On graphs depicting results of these experiments, each point shows the arithmetic mean magnitude of wear, which was determined from two pairs of samples simultaneously tested in each of the two working cavities of the stand. On the graphs and in the figure captions the following designations are accepted: u_1 and u_2 - intensity of wear of the guide and slider respectively; $И_1$ and $И_2$ - integral weighed wear of the guide and slider, respectively; $И_с$ - mean integral weighted wear one natural sample; $И_м$ - mean integral weighted wear of one coupling; $И_{тр}$ - mean integral weighted wear of one sample of a pipe; S - path of friction of the slider; v - speed

of slip of the slider; p - nominal specific pressure; t - duration of friction; c - concentration of solution, u_1/u_2 = A.

From Fig. 3 one can see that at a specific pressure of 3.3 kg/cm^2 and with friction in sea water contracting the air, an increase in ratio F_2/F_1 from 0 to 8 corresponds approximately to a triple increase in intensity of the wear of the guide. At the same time the intensity of wear of the slider was increased by only 18%, and the ratio of magnitudes of wear of the guide and slider was increased from 13.8 to 35.3.

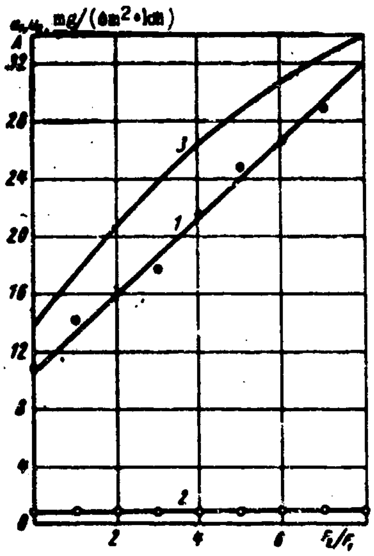


Fig. 3. Dependence of wear of samples of normalized steels 45 on the area of a nonrubbing part (friction in sea water coming into contact with the air, S = 24 km; v = 0.66 m/s; p = 3.3 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of guide to wear of the slider.

Let us discuss this very interesting phenomenon in more detail.

The effect of absolute dimensions of two conjugate surfaces on the ratio of magnitudes of their wear with sliding friction was investigated by N. Garkunov. From his work [8] it is clear that in the manufacture of both elements of the friction pair from the same steels the sample with the large surface is worn out more than the sample with the smaller surface. This regularity, observed independently of load and the presence of abrasive, D. N. Garkunov explains in the following way. In the absence of the transfer of material from one rubbing surface to the other and with oxidation of the surface, the mechanical wear of them should be considered as a

continuous destruction of separate "weak places" of spots of contact. With movement of a small sample after destruction of the existing "weak places," on its surface such places are again formed. However, the per unit of area of friction of them will be less than the per unit of area of friction of a large sample, since for their formation a certain finite time is required. Proof of the validity of such an explanation is perceived in the fact that with the lowering of the rate of slip down to 1 m/h the curve on Fig. 4 becomes more sloping, cutting off of the axis of the ordinates a segment equal to unity.

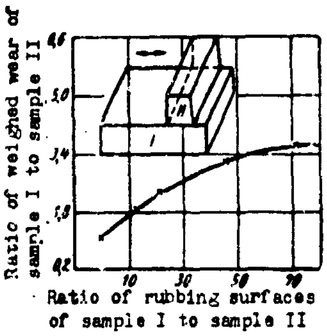


Fig. 4. Dependence of ratio of magnitudes of the wear of steel samples on the magnitude of the ratio of their surface of friction (after D. N. Garkunov) [8].

In experiments conducted by the authors the ratio of surfaces of friction of the guide and slider was equal to 20. With such a degree of overlap of the samples, according to Fig. 4, one would expect that the intensity of wear of the guide will exceed approximately 2-2.5 times the intensity of wear of the slider. However, as one can see (see Fig. 3), the ratio of magnitudes of wear even at F_2/F_1 equal to zero was 13.8, which considerably exceeds the ratio of magnitudes of wear obtained in work [8].

The divergence between results of the experiments described and data [8] is quite regular if one were to consider that in experiments of D. N. Garkunov electrochemical corrosion of rubbing surfaces was absent, and in the experiments described it not only took place, but was one of the factors determining the mechanism and regularity of the process of wear. This mechanism can be represented in the following form.

With slip of the short slider along a sufficiently long guide, the whole surface of friction of the slider is in contact with the guide during the whole duration of the experiment. At the same time each element of the rubbing surfaces of the guide with an area equal to the area of the slider comes into contact with the latter only during a time equal to the duration of the experiment, multiplied by the degree of overlap of the samples. Thus, for instance, in the experiments described the slider was in contact with the guide for 10 h, and each element of the rubbing surfaces of a guide with a length equal to the length of the slider, i.e., 1 cm came into contact with slider for a total of 0.5 h. During the other 9.5 h the rubbing surfaces of the guide was subjected to electrochemical corrosion, which occurred very intensely in view of the fact that products of it were continuously destroyed and departed by the moving slider. At the same time owing to hampered access of the corrosion medium into the gap between elements of the friction pair, the rubbing surfaces of the slider corroded to a considerably lesser degree.

The unequal effect of electrochemical corrosion on each of the conjugate rubbing surfaces is the cause of the different wear of these surfaces, and, consequently, the fact that the ratio of magnitudes of the wear of the guide and slider is larger than with friction of the same samples in a noncorrosive medium.

In view of the described mechanism of mutual corrosion-mechanical wear of steel in solutions of neutral salts, the cause of the growth of the ratio of magnitude of wear of the guide and slider with an increase in ratio F_2/F_1 becomes quite clear. It consists in the fact that an increase in the surface F_2, i.e., the macrocathode, conditioning the substantial increase in corrosion rate of the rubbing part of the surface of the guide, also causes strong intensification of wear of it. At the same time the wear of the slider is changed comparatively little with an increase in ratio F_2/F_1, since the rubbing surface of it, in general, corrodes to a considerably lesser degree than does the rubbing surface of the guide. Furthermore, considering data of [46], one can assume that

with a very thin layer of the electrolyte available in the gap between elements of the friction pair, distant parts of the uncleaned surface of guide cease to be an effective cathode for the rubbing surfaces of the slider.

Other results were obtained in the carrying out of the same experiments but at a specific pressure of 13.4 kg/cm^2. From Fig. 5 it is clear that with an increase in the ratio F_2/F_1 from 0 to 8 the intensity of wear of the directing was increased a total 32%, whereas at a specific pressure of 3.3 kg/cm^2 and other identical conditions it increased approximately three times. At a specific pressure of 13.4 kg/cm^2 the wear of the slider also little depends on the magnitude of ratio F_2/F_1. Therefore, at the indicated increase in ratio F_2/F_1, the ratio of magnitudes of wear of the guide and slider increased a total of 22%.

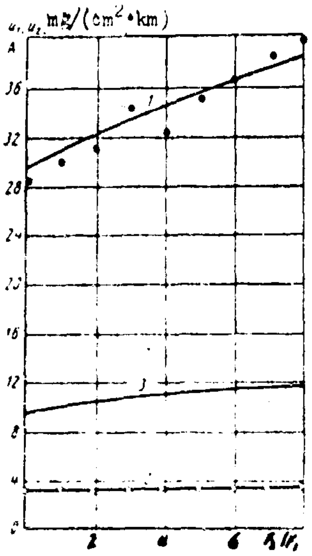


Fig. 5. Dependence of wear of samples of normalized steels 45 on the area of the nonrubbing part of the guide (friction in sea water coming into contact with air, S = = 24 km; v = 0.66 m/s; p = 13.4 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of guide to wear of the slider.

Figure 6 shows the dependence of the intensity of wear of samples on ratio F_2/F_1 with friction in deoxygenated sea water. The experiment was conducted at a specific pressure of 3.3 kg/cm^2. A change in ratio F_2/F_1 from 0 to 8 corresponds to an increase in intensity of wear of the guide of 24%. The intensity of wear of the

slider was practically not changed, and the ratio of magnitudes of wear of the guide and slider was increased from 8 to 9.7.

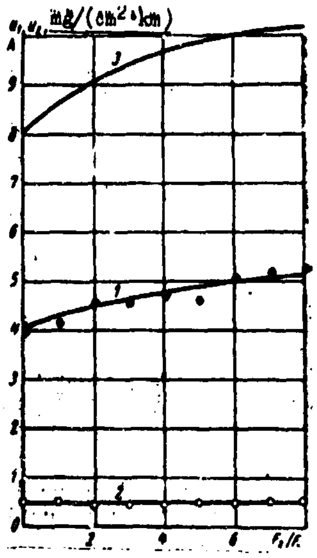


Fig. 6. Dependences of wear of samples of normalized steels 45 on the area of the nonrubbing part of the guide (friction in deoxygenated sea water, S = 24 km; v = 0.66 m/s; p = 3.3 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider

At a specific pressure of 13.4 kg/cm^2 an increase in ratio F_2/F_1 from 0 to 8 almost did not affect the intensity of wear of the samples in deoxygenated sea water.

The comparatively small effect of ratio F_2/F_1 on the intensity of the mutual wear of steel samples in deoxygenated solutions of neutral salts even at small values of specific pressure is regular, inasmuch as the perceptible effect of the magnitude of the area of the cathode on the rate of electrochemical corrosion is observed mainly for corrosion processes occurring with oxygen control.

The effect of ratio F_2/F_1 on the intensity of the mutual wear of steel samples was investigated also with frictions of them in a 3% NaCl solution. Results of these experiments are not given here, since they are quite similar to results obtained in sea water.

A general conclusion ensuing from an analysis of results of the above experiments is the fact that independently of factors controlling the electrochemical corrosion of steel in neutral salt solutions, the corrosion factor determines the intensity of wear

only at small values of specific pressure. At comparatively large values of specific pressure the role of the mechanical factor in the process of corrosion-mechanical wear sharply increases, and the relative effect of the corrosion factor decreases.

Here we are now limited only by the ascertainment of this fact. Results of the investigation of physical causes determining it are given below in the course of the description of regularities of mutual wear of steel with friction in solutions of neutral salts.

3. Regularities of Mutual Wear of Steel with Friction in Solutions of Neutral Salts

The dependence of the intensity of wear on the means of friction. In reference to the wear of steel with friction of it against the abrasive surface in certain corrosive liquids, this problem was first investigated by M. M. Khrushchov and M. A. Babichev. Results of experiments described in work [43] showed that with the wiping on steel samples of a crater with the help of a disk possessing abrasive properties, the connection between volumetric wear and the duration of friction with a constant rate in distilled water and a 0.5% solution of K_2CrO_4 is depicted by a straight line. Analogous results were obtained for steel 20 and steel 45 with friction in NaOH solutions with a concentration not exceeding 10% [5].

Results of experiments conducted by authors in reference to the mutual wear of steel with friction in neutral salt solutions are given on Fig. 7.

With friction in sea water making contact with air, the constancy of the intensity of wear with time is observed not from the very beginning of the experiment, but from a certain moment of time not identical for the guide and slider.

The constancy of the intensity of wear of the guide with time comes approximately after 2 h, and the straightening of the graph of

wear of the slider is observed only after 3 h from the moment of the beginning of the experiment, in spite of the fact that path of friction of the slider is 20 times more then the path of friction of every element of the surface of contact of the guide with the length equal to the length of the slider. A similar phenomenon is observed also with friction in a 3% NaCl solution

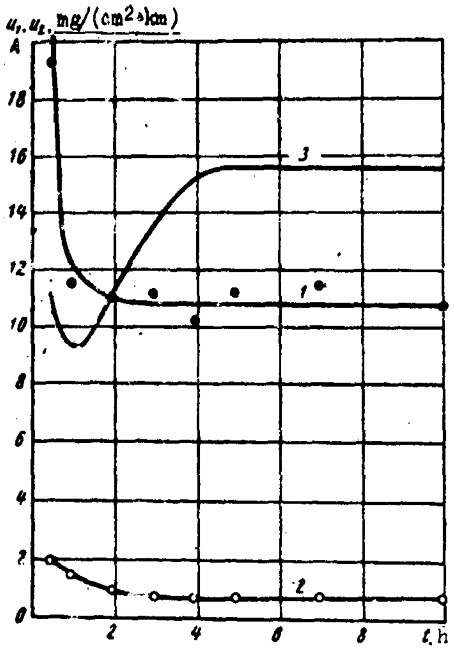


Fig. 7. Dependence of the wear of samples of normalized steels 45 on path of friction of sea water making contact with air (v = 0.66 m/s; p = 3.2 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

It is obvious that initial sections of graphs on Fig. 7 reflect the process of running-in of conjugate rubbing surfaces. In this respect the results obtained are qualitatively identical to results of the investigation of other forms of wear [45]. However, the nature shown on Fig. 7 of the change in the ratio of magnitudes of wear of the guide and slider in the process of running-in of elements of the pair noticeably differs from that observed with friction in noncorrosive liquids.

According to [8], in the absence of a corrosion medium in the beginning of the period of running-in the wear of the slider is greater than the wear of the guide. At the end of this period the ratio of magnitudes of wear of the guide and slider becomes larger

than unity and remains such during tests of any duration. D. N. Garkunov explains such redistrubution of magnitudes of wear by the fact that in the process of running-in, the magnitudes of area of contact is changed in disproportion to nominal rubbing surfaces of each of the elements of the pair. In the initial period of running-in the actual surface of friction of the guide, since the last was run-in to a lesser degree, and on it there were wave crests. In the subsequent period of running-in the actual area of friction of the guide becomes larger than the area of friction of the slider.

The running-in of surfaces of friction under conditions of corrosion-mechanical wear occurs differently. Being here and there of intense electrochemical corrosion, wave crests and roughnesses on the rubbing surface of the guide are rapidly destroyed, and products of corrosion depart by the moving slider. The latter, in turn, causes an intensification of the corrosion and, finally, greater wear of the rubbing surface of the directing from the very beginning of the period of running-in. At the same time the smoothing of the rubbing surface of the slider proceeds slower, inasmuch as it corrodes not so intensely. For reasons the ratio of magnitudes of wear of the guide and slider are larger than unity from the very beginning of the process of running-in.

The described scheme of running-in of rubbing surfaces with corrosion-mechanical wear is confirmed by results of experiments conducted by the same method with a deoxygenated solution of neutral salts. In the absence of the access of oxygen to the rubbing surfaces, the extent of the curvilinear section of the graph of wear of the slider was almost not changed. The period of running-in of the guide in a liquid coming into contact with the air is less than the period of running-in of it in a deoxygenated liquid; the ratio of magnitudes of wear of the guide and slider in this case considerably decreases. The cause of these changes consists in the fact that in the absence of the access of oxygen corrosion of the rubbing surface of the guide was delayed, and condition of wear of the slider were changed to a considerably lesser degree.

Effect of the rate of slip and specific pressure. The effect of the rate of slip on the intensity of wear of metals in conditions of dry friction and threshold lubrication is the subject of a number of investigations. For conditions of the wear of steel with friction in neutral salt solutions this dependence is not studied.

In the region of dry friction the effect discovered by Ye. Kel' and Ye. Zibel' of the intermittent decrease in wear with an exceeding of the rate of slip of the defined "critical" magnitude is known. I. V. Kragel'skiy and Ye. M. Shvetsov, who confirmed the presence of this effect, established that the intermittent decrease in wear in the region of "critical" rate of slip is caused by a qualitative change in the nature of destruction of the rubbing surfaces [20]. Investigations of V. I. Kostetskiy and P. K. Topekha showed that with dry friction in the speed range of slip of 0.14-25.0 m/s there is not one but several "critical" points limiting regions of the existence of different forms of wear with the state of the rubbing surfaces and structure of surface layers of metal peculiar to each of them [38, 18]. According to data of M. M. Khrushchov, in the presence of a lubricant on rubbing surfaces the intensity wear of cast iron sharply increases with an increase in rate of slip and specific pressure [41].

In the region of dry friction and in noncorrosive liquids an increase in specific pressure almost always causes an intensification of wear. There are cases when the wear intermittently increases at definite values of specific pressure. From Fig. 8 one can see [38] that with dry friction in an air medium an increase in specific pressure noticeably reduces the speed range of slip, within limits of which the oxidizing wear of steel is observed. At the same time from these graphs it follows that in the region of oxidizing wear, characterized by minimum material losses, the specific pressure practically does not affect the wear.

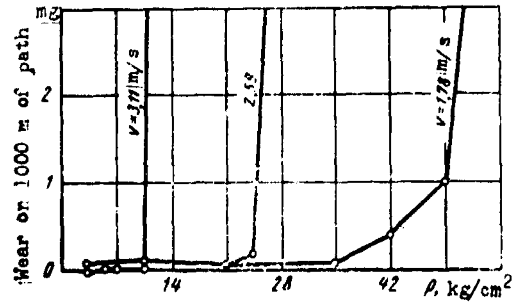


Fig. 8. Dependence of wear of heat-treated steels U10A on specific pressure (after P. K. Topekha)

The effect of specific pressure on the intensity of corrosion-mechanical wear of metals and alloys is very weakly studied. According to work [40], the corrosion-mechanical wear of gray cast iron is directly proportional to the specific pressure up to a certain magnitude of the latter, after which the magnitude of wear sharply increases. For alloyed cast iron a more complicated dependence of wear on specific pressure is observed. The increase in intensity of the wear of cast iron with the increase in specific pressure is explained not only by the intensification of the mechanical factor, but also by the fact that with the growth of specific pressure cold hardening of surface layers of the metal is increased and their chemical activity increases. Certain data on the effect of specific pressure on the intensity of the wear of steel with friction in solutions of alkalis are contained in the work of I. V. Vasil'yev. Experiments conducted by him on the machine Kh2-M showed that with an increase in the concentration of the alkali the value of "critical" load increases at which "grasping" of the rubbing surfaces occurs, and the pressure is increased at which the increase in volume of the crater of wear is ceased [5].

To study the effect of the rate of slip and specific pressure on the intensity of the mutual wear of steel with friction in neutral salt solutions two series of experiments are conducted by the authors: with an identical path of friction and w[illegible] an identical duration of friction. Inasmuch as during the operation of the majority of contemporary units of friction found under the effect of corrosive liquids, the rate of slip oscillates within 0.1-1.0 m/s, and the effect of rate of slip of the intensity of wear of the samples was also studied in this speed range.

Experiments conducted with constant path of friction showed that at the given value of specific pressure the shape of the curve depicting the dependence of the intensity of wear on the rate of slip is approximately identical for the guide and slider. The difference is only that the absolute value of the intensity of wear and rate of its change depending upon the rate of slip for the guide is considerably larger than that for the slider.

From Fig. 9 it is clear that, although in the considered speed range of slip and specific pressures the intensity of wear of the samples decreases with an increase in the rate of slip, an intermittent decrease in wear is not observed.

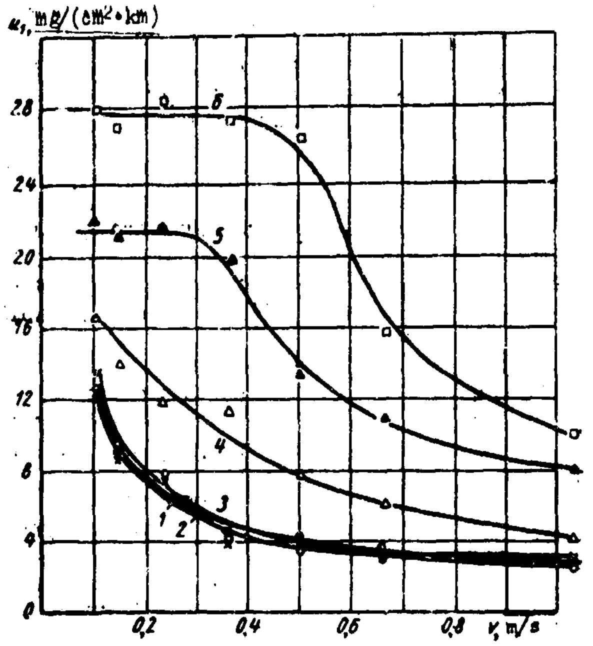


Fig. 9. Dependence of the wear of samples of normalized steels 45 on the rate of slip with identical path of friction in deoxygenated sea water (S = 57 km): 1 - p = 0.5 kg/cm^2; 2 - p = 3.2 kg/cm^2; 3 - p = 6.6 kg/cm^2; 4 - p = 9.4 kg/cm^2; 5 - p = 12.2 kg/cm^2; 6 - p = 15.1 kg/cm^2.

The form of the graphs of wear is not identical for all values of specific pressure. In the region of comparatively low values of specific pressure, a continuous decrease in the intensity of wear with an increase in the rate of slip is observed. Curves obtained for the value of specific pressure of 0.5, 3.2 and 6.6 kg/cm^2 practically coincide. The latter indicates that the magnitude of specific pressure up to a defined limit affects the intensity of wear

little. At specific pressures exceeding 6.6 kg/cm^2, the intensity of wear in the whole considered speed range of slip noticeably increases, and the character of the curves itself is changed. On graphs almost a horizontal initial section is observed, the extent of which is greater, the higher the specific pressure. Beyond the limits of this section the intensity of wear is noticeably reduced.

The unequal form of graphs of wear, which were obtained for different values of specific pressure, is conditioned by the different nature of destruction of the rubbing surfaces.

At small values of specific simple mechanical removal of products of corrosion occurs from the rubbing surface of the guide. A decrease in intensity of wear with an increase in rate of slip here is conditioned exclusively by the fact that with an identical path of friction the duration of the effect of the corrosion medium on metal and, consequently, the quantity of the corroded metal are inversely proportional to the rate of slip. Strictly speaking, in the case when an increase in the thickness of the layer of products of corrosion with time occurs according to the law distinguished from the linear, the direct ratio of the quantity of corroded metal and duration of the experiment should not be observed. However, considering the short duration of time occurring between two adjacent movements of the slider, one can assume that the process of electro-chemical corrosion of the rubbing surface of the guide is described by initial sections of corrosion-time curves. As is known, the form of these sections at any law of the growth of the oxide film in partice differs little from a straight line.

From Fig. 10 it is clear that if with an identical path of friction we examine the intensity of wear as a function of only duration of the experiment, which is in this case is a quantity inversely proportional to the rate of slip, then at specific pressures of 0.5-6.6 kg/cm^2 graphs of this function have the form of straight lines, which in practice coincide in the whole interval of applied rates of slip.

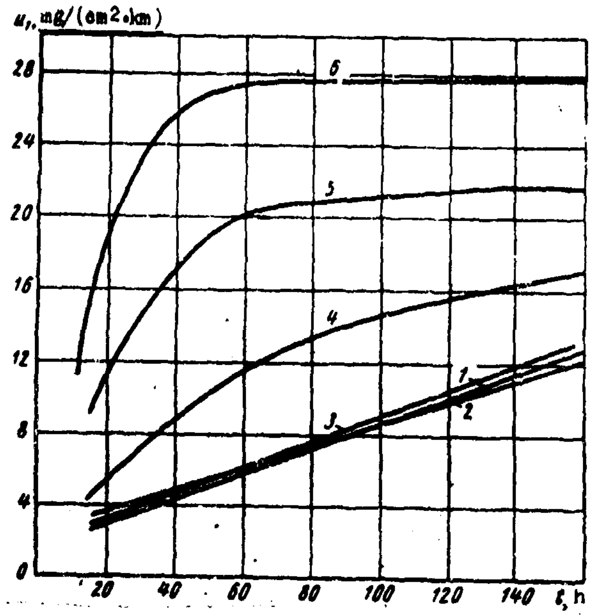


Fig. 10. Dependence of the wear of samples of normalized steels 45 on the duration of the experiment with an identical path of friction in deoxygenated sea water (S = 57 km): 1 - p = 0.5 kg/cm^2; 2 - p = 3.2 kg/cm^2; 3 - p = 6.6 kg/cm^2; 4 - p = 9.4 kg/cm^2; 5 - p = 12.2 kg/cm^2; 6 - p = 15.1 kg/cm^2.

The rubbing surfaces of samples tested specific pressures of 0.5-6.6 kg/cm^2 are covered by a uniform layer of products of corrosion. Traces of the "grasping" of the metal at any of the applied rates of slip is not observed (Fig. 11). Plastic deformation of surface layers of the metal is absent. The hardness of these layers in no way differ from the hardness of the remaining metal.

At specific pressures exceeding 6.6 kg/cm^2, the form of the rubbing surfaces is changed. On Fig. 12 it is possible to see that at rates of slip of 0.1-0.5 m/s, local destructions of the layer of products of corrosion occur at the whole depth accompanied by "grasping" of the surfaces. In places "grasping" plastic deformation of surface layers of the metal is observed. At rates of slip exceeding 0.5 m/s. The number of sections of complete destruction of the layer of products of corrosion decreases. On Fig. 13 it is shown that the shape of the surface of friction of the guide tested at a specific pressure of 15.1 kg/cm^2 and rate of slip of the slider 1.04 m/s approaches the form observed at a specific pressure of 3.2 kg/cm^2.

Let us consider the effect of the rate of slip on the ratio of magnitudes of wear of the guide and slider.

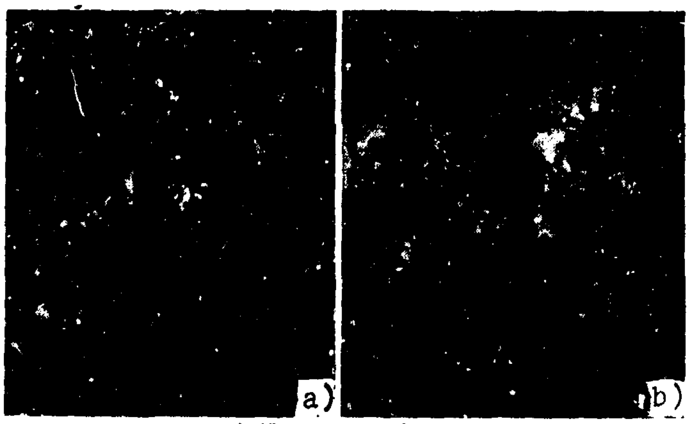


Fig. 11. Photomicrograph of the rubbing surface and microstructure of surface layers of metal of the sample (guide) of normalized steels 45 tested for wear with friction in deoxygenated sea water (v = 0.66 m/s, p = 3.2 kg/cm^2): a) rubbing surface ×60; b) microstructure, ×100.

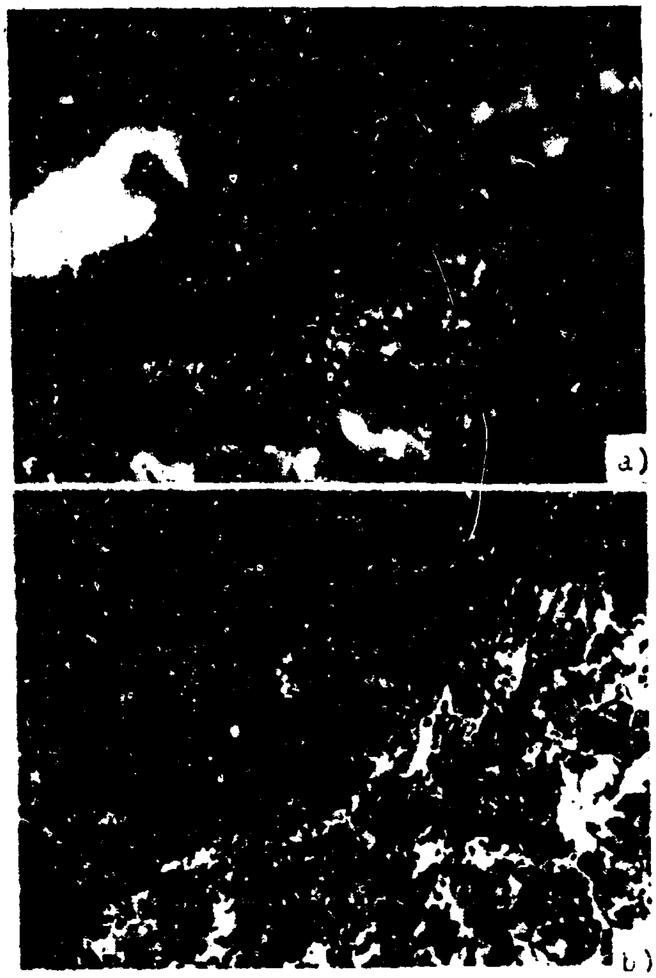


Fig. 12. Photomicrograph of the rubbing surface and microstructure of surface layers of a sample of normalized steels 45 (guide) tested for wear with friction in deoxygenated sea water (v = 0.23 m/s, p = 15.1 kg/cm^2): a) the rubbing surface, ×60; b) microstructure, ×100.

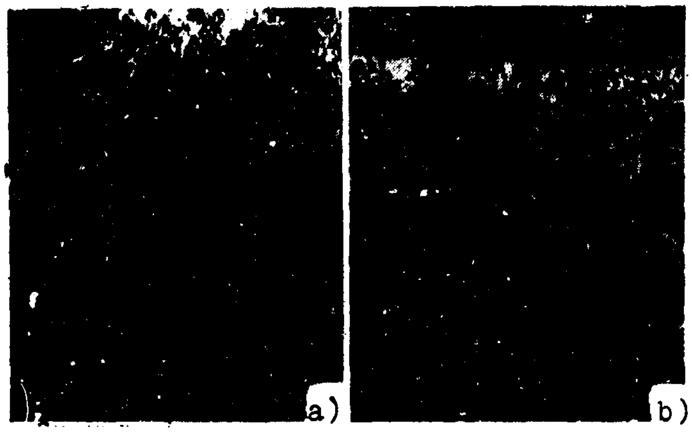


Fig. 13. Photomicrograph of the rubbing surface and microstructure of surface layers of a sample of normalized steels 45 (guide) tested for wear with friction in deoxygenated sea water (v = 1.04 m/s, p = 15.1 kg/cm^2): a) surface of friction, ×60; b) microstructure, ×100.

Earlier it was indicated that in the absence of the oxidation of rubbing surfaces, the magnitude of this ratio decreases with a lowering of the rate of slip [8]. As can be seen from Fig. 14, with the mutual wear of steel in a deoxygenated solution of neutral salts a reverse pattern is observed: the ratio of magnitudes of wear of the guide and slider decreases with an increase in the rate of slip, and this appears especially at low values of specific pressure when the process of wear is controlled by corrosion phenomena occurring on the rubbing surface of the guide.

Let us note that results of the experiments described give no basis to consider immaterial the effect of corrosion on the intensity of the mutual wear of steel with friction in a corrosive liquid medium at relatively high values of specific pressure. Conversely, in the presence of "grasping" of the rubbing surfaces and plastic deformation of surface layers of the metal, the rate of electrochemical corrosion increases. However, relative the effect of corrosion decreases, since the role of the mechanical factor in the process of

wear increases with an increase in specific pressure up to a value sufficient for complete destruction of the layer of products of corrosion on the rubbing surfaces.

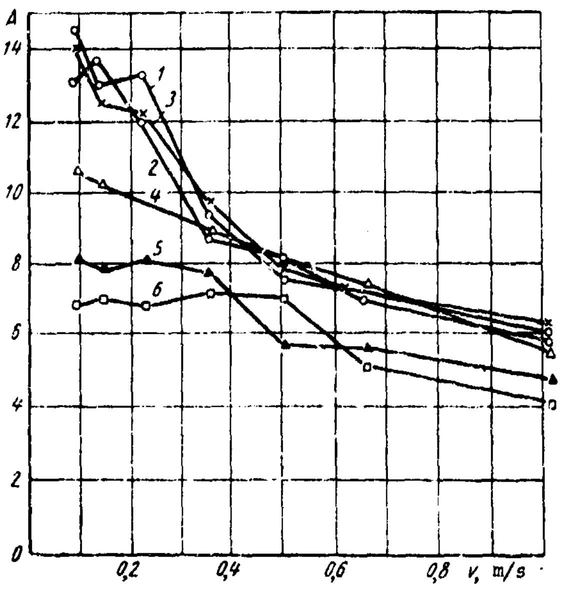


Fig. 14. Dependence of the ratio of the magnitude of wear of the guide and slider prepared from normalized steels 45, on the rate of slip with an identical path of friction in deoxygenated sea water (S = 57 km): 1 - p = 0.5 kg/cm^2; 2 - p = 3.2 kg/cm^2; 3 - p = 66 kg/cm^2; 4 - p = 9.4 kg/cm^2; 5 - p = 12.2 kg/cm^2; 6 - 15.1 kg/cm^2.

For the complete elucidation of the question, let us examine results of experiments illustrating the effect of the rate of slip on the intensity of mutual corrosion-mechanical wear of steel samples with identical duration of the experiment.

One series of experiments was conducted at a specific pressure of 3.3 kg/cm^2 and a second - at 13.6 kg/cm^2. The duration of each experiment was 10 h, not counting the time of the running-in of friction pairs. The path of friction of the slider at a rate of slip of 0.1 m/s was 3.6 km, and at a speed of 1.04 m/s – 37.4 km.

From Fig. 15 it is clear that at a specific pressure of 3.3 kg/cm^2 the intensity of wear of the samples does not depend on the rate of slip. Consequently, in the region of low values of specific pressure with an identical duration of the interaction of rubbing surface with the working medium, the rate of slip itself within limits of the considered speed range does not have a noticeable effect on the intensity of the corrosion-mechanical wear of samples.

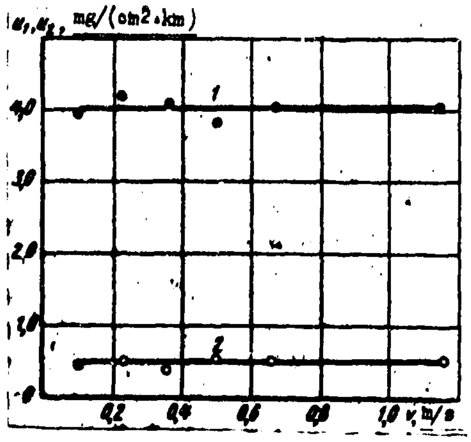


Fig. 15. Dependence of the wear of samples of normalized steels 45 on the rate of slip with identical duration of friction in deoxygenated sea water ($t = 10$ h, $p = 3.3$ kg/cm^2): 1 - guide; 2 - slider.

At a specific pressure of 13.6 kg/cm^2 the dependence of the intensity of wear on the rate of slip is depicted by a curve with a maximum corresponding to the rate of 0.5 m/s (Fig. 16).

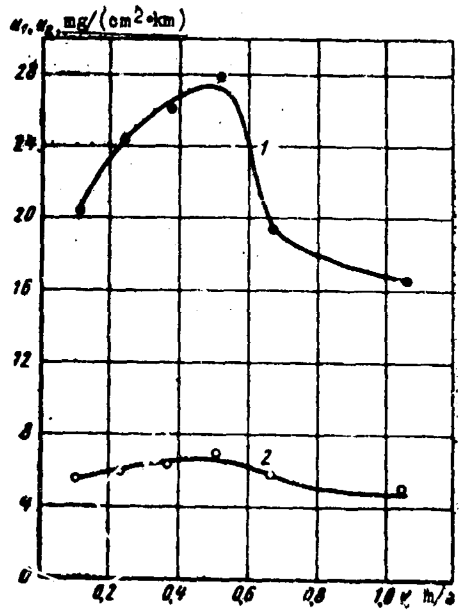


Fig. 16. Dependence of the wear of samples of normalized steels 45 on the rate of slip with an identical duration of friction in deoxygenated sea water ($t = 10$ h, $p = 13.6$ kg/cm^2): 1 - guide; 2 - slider.

Thus, it is confirmed that in the region of comparatively high values of specific pressure which conditioned the destruction of the layer of products of corrosion, the role of the rate of slip noticeably increases.

Effect of the method of change in specific pressure. In operational conditions the conjugate parts can wear out at constant load and variable specific pressure, which change with an increase or reduction in the area of contact. This is possible, for instance, with mutual wear of two cylindrical parts according to the diagram shown on Fig. 17. Therefore, the investigations of laboratory samples which are worn out in analogous conditions was of interest.

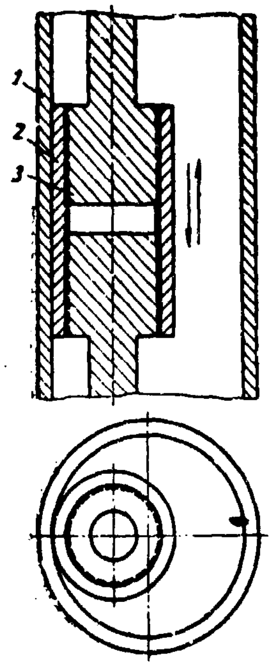


Fig. 17. Diagram of the wear of pump pipes and rod couplings in petroleum deep pumping wells: 1 - pump pipe; 2 - rod coupling; 3 - pump rods.

To study this question, authors conducted a series of experiments. In all six experiments making up the series, the load on the samples was constant and equal to 6.8 kg. The length of the guide and slider was equal, respectively, to 210 and 10 mm. The width of the samples was 10, 15, 20, 35, 50 and 80 mm, which at a given load corresponded to specific pressures of 6.80, 4.53, 3.40, 1.94, 1.36 and 0.86 kg/cm^2.

Results of the experiments are shown in Fig. 18. For convenience of comparison, the dependence of the wear of samples on specific pressure at variable load and constant dimensions of the rubbing surface is also given. From the graphs it is clear that

independently of the method of change in specific pressure, the magnitude of latter is defined limits affects very little the intensity of the mutual corrosion-mechanical wear of steel. This gives the basis to make in practice an important conclusion concerning the mutual wear of two cylindrical parts with friction in a corrosive liquid medium: if the initial specific pressure was insufficient for the full destruction of the layer of products of corrosion, which is formed on rubbing surfaces under the effect of the working medium, the intensity of linear wear practically will not be lowered with time, in spite of the continuous lowering of the specific pressure, conditioned by an increase in the area of contact between elements of the friction pair. Due to this, at constant speeds and load, the magnitude of the integral weighted wear will be proportional to the duration of friction to a degree larger than unity. Figure 19 shows that in the region of low values of specific pressure the magnitude of the integral weighted wear of samples is determined by the nominal magnitude of the rubbing surface.

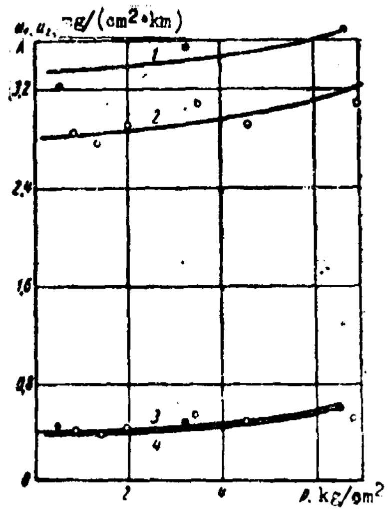


Fig. 18. Dependence of the wear of samples of normalized steels 45 on specific pressure with friction in deoxygenated sea water (S = 57 km, v = = 0.66 m/s): 1 and 2 - guide; 3 and 4 - slider; 1 and 3 - at variable load and constant magnitude of the rubbing surface and constant load.

Effect of the hardness of steel. Source data on the effect of hardness of steel on the resistance to wear of it with friction in corrosive liquids are not numerous and are contradictory.

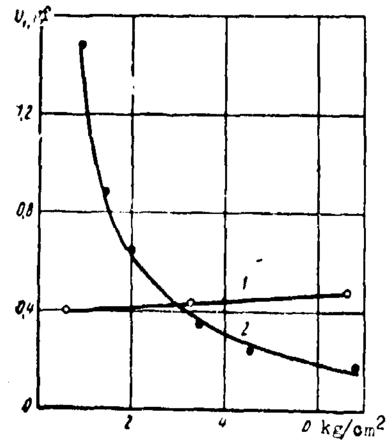


Fig. 19. Dependence of the integral weighted wear of samples from normalized steels 45 (guide) on specific pressure with friction in deoxygenated sea water (S = 57 km, v = 0.66 m/s): 1 - with variable load and constant magnitude of rubbing surface; 2 - with variable magnitude of rubbing surface and constant load.

From data given in work [13], it can be concluded that with friction to tap water, acidified by sulfuric acid up to pH = 4.18, the resistance to wear of rail steels is proportional to the hardness number changeable by means of heat treatment to a degree larger than unity. With friction in NaOH solutions with a concentration of not more than 15%, steel 20 possesses an increased resistance to wear as compared to steel 45, in spite of the greater hardness of the latter. In the region of higher concentrations of alkali the reverse is observed (Fig. 20) [5]. In work [44] it is shown that the dependence of the resistance to wear of carbon steel on the hardness of it is not identical for different states of the material and working media. The connection between the resistance to wear of annealed unalloyed steel and the hardness of it is described by a curve with a maximum both with friction in distilled water and in a 0.5% K_2CrO_4 solution. The resistance to wear of the same brands of steel subjected to gas chrome plating, which changes not only the hardness of the surface layers but the nature of them, is in a rectilinear dependence on hardness in both indicated corrosion media.

An investigation of the dependence of the intensity of mutual wear of carbon steel on hardness with friction in solutions neutral salts was conducted by authors on samples of steel in a state of delivery. Hardness of the steel was changed depending upon content of carbon in it:

Carbon content in %.......	0.18	0.32	0.44	0.59	0.76	0.88
HB.....................	146	176	212	251	284	301

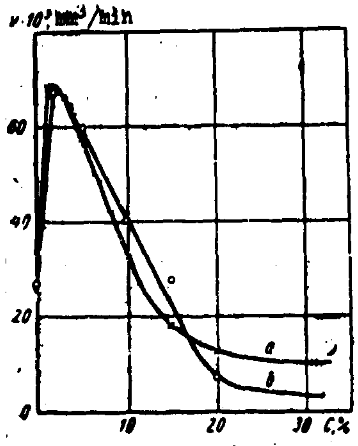


Fig. 20. Dependence of wear of unalloyed steels on the concentration NaOH: a) steel 20; b) steel 45.

Experiments were conducted at specific pressures of 3.3 and 13.1 kg/cm^2. For every value of specific pressure two series of experiments were conducted: variable hardness of the guide and constant hardness of the slider and constant hardness of the guide and variable hardness of the slider.

From Fig. 21 it is clear that at a specific pressure of 3.3 kg/cm^2 and constant hardness of the slider (HB 212), an increase in hardness of the guide from HB 146 to HB 235 does not cause a perceptible change in the intensity of wear of it. A further increase in hardness of the guide up to HB 301 corresponds to a certain increase in the intensity of wear of it. The intensity of wear of the slider at a given value of specific pressure does not depend on the hardness of the guide.

Results of these experiments explained well with the help of a sufficiently studied dependence of the speed of the electrochemical corrosion of steel in neutral salt solutions on the content of carbon in it. It is known that carbon in a quantity of up to 0.5% does not affect the corrosion rate in these solutions. At higher contents of carbon a certain increase in the corrosion rate is observed [26].

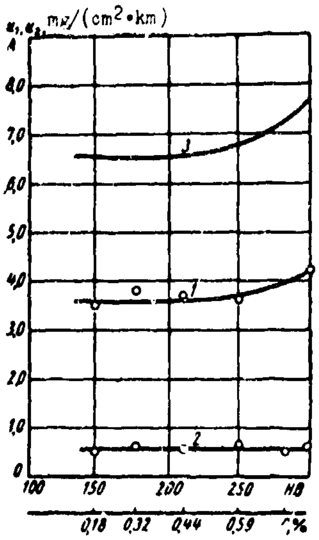


Fig. 21. Dependence of the wear of samples of normalized steels 45 on the hardness of the guide at constant hardness of the slider HB 212 (friction in deoxygenated sea water. S = 24 km, v = 0.66 m/s, p = 3.3 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

From Fig. 21 it is clear that a certain increase in intensity of wear of the guide is observed with a hardness of it corresponding to the content of carbon equal approximately to 0.54%. It is obvious that at low values of specific pressure the character of the graph of wear of the guide is conditioned by exceptionally corrosion processes occurring on its rubbing surface.

Absence of the effect of hardness of the guide on the intensity of wear of the slider is also regular. It is known that composition of products of corrosion of unalloyed steel is determined basically by the type of the corrosion medium and in practice does not depend on the content of carbon and mechanical factors affecting the metal in the process of electrochemical corrosion [26]. Therefore, coming into contact with the layer of products of corrosion, which covers the surface of friction of the guide, and not with the metal itself from which it is prepared, the slider is worn out equally with a different content of carbon in the guide and, consequently, also with a different hardness of it.

Mutual wear of the same samples at a specific pressure of 13.1 kg/cm^2 and other identical conditions occurs differently. From Fig. 22 it is clear that at this value of specific pressure, an increase in hardness of the guide from HB 146 to HB 301 corresponds

to perceptible decrease in the intensity of wear of it. Together with this a noticeable intensification of wear of the slider having a constant hardness is noted.

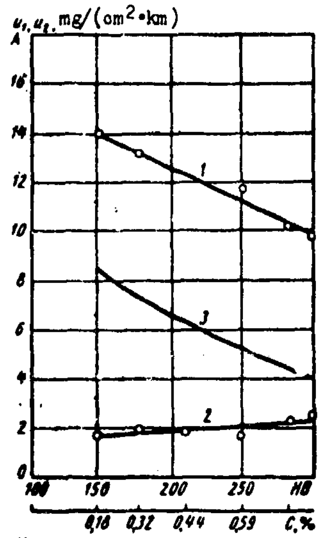


Fig. 22. Dependence of wear of samples of normalized steel 45 on the hardness of the guide with constant hardness of the slider HB 212 (friction in deoxygenated sea water. S = 24 km, v = 0.66 m/s, p = 13.1 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

Thus, at specific pressures sufficient for destruction of the layer of products of corrosion on the rubbing surface of the guide, the hardness of elements of the friction pair, just as other mechanical factors, obtains an substantial value.

Experiments conducted with a constant hardness of the guide and variable hardness of the slider showed that, independently of the specific pressure, the resistance to wear of the slider increases approximately in conformity with the hardness of it. In this case in the region of low values of specific pressure, a change in hardness of the slider does not change a noticeable change in intensity of wear of the guide (Fig. 23). At a specific pressure of 13.1 kg/cm^2 an increase in hardness of the slider together with an increase in resistance to the wear of it was accompanied by the intensification of wear of the guide (Fig. 24).

We do not discuss the analysis of results of experiments given on Figs. 23 and 24, since they are sufficiently clear from the description of experiments conducted with variable of hardness of

the guide and constant hardness of the slider. Let us underline only the fact that the hardness of the slider is a factor determining its resistance to wear independently of the magnitude of specific pressure. This is an additional confirmation of the earlier drawn conclusion concerning the essential distinction in conditions of wear of the guide and slider with friction in solutions of neutral salts.

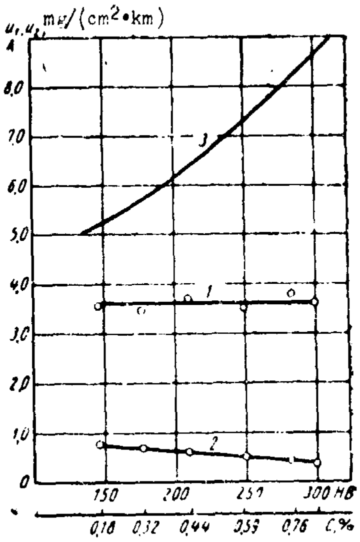


Fig. 23.

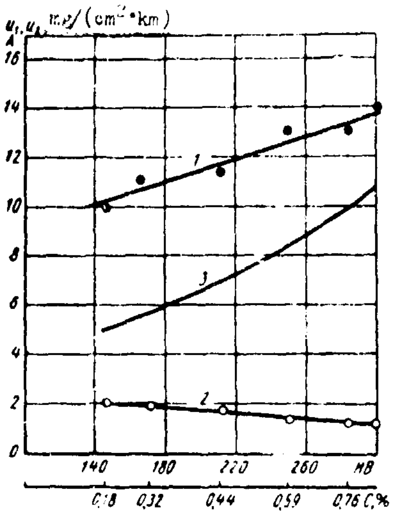


Fig. 24.

Fig. 23. Dependence of wear of samples of normalized steels 45 on the hardness of the slider with constant hardness of the guide HB 212 (friction in deoxygenated sea water. S = 24 km, v = 0.66 m/s, p = 3.3 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

Fig. 24. Dependence of wear of samples of normalized steels 45 on the hardness of the slider with constant hardness of the guide HB 212 (friction in deoxygenated sea water. S = 24 km, v = 0.66 m/s, p = 13.1 kg/cm^2): 1 - guide; 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

The influence of temperature of the medium. To study the mechanism of wear of steel in solutions of neutral salts, it is of interest whether the action of other factors stimulating the electro-chemical corrosion of steel is similar to the action of oxygen (see Section 2 of this chapter). Let us examine the [illegible] of [illegible]

of the medium. From Fig. 25 it is clear that the temperature of deoxygenated sea water greatly affects the intensity of wear of guide and to a considerably smaller degree the intensity of wear of the slider.

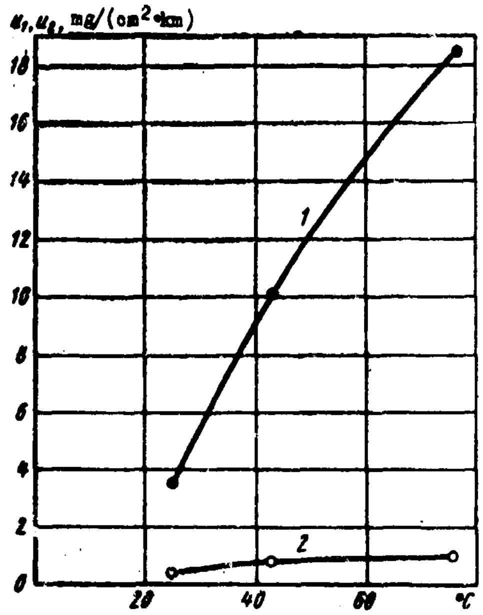


Fig. 25. Dependence of the wear of samples of normalized steels 45 on the temperature of the medium with friction in deoxygenated sea water (S = 24 km, v = 0.66 m/s, p = 3.3 kg/cm^2): 1 - guide; 2 - slider.

It is necessary to note that the effect of the temperature of the mutual wear of steel in the mentioned corrosion medium condition substantially differs from the effect of it in nonelectrolytes.

With an increase in temperature of the noncorrosive medium, the wear of the slider is increased to a greater degree than the wear of the guide [8]. The temperature increase in the neutral salt solution, increasing the rate of flow of the corrosion processes on the rubbing surface of the guide, causes an intensification of wear of it. On the surface of the slider electrochemical corrosion occurs with considerably less speed. Therefore, an increase in temperature of the corrosion medium, just as other factors which stimulate the electrochemical corrosion, increases the ratio of magnitudes of wear of the guide and slider

Characteristic in this respect are results of experiments conducted by the authors for studying the joint effect of temperature

and oxygen on the rubbing surface. Conditions of carrying out the experiment differed from the preceding only by the fact that the flowing water made contact with the air before entering into the working cavity of the stand. From Fig. 26 it is clear that under these conditions the dependence of the wear of samples on the temperature is depicted by a curve with a maximum. The same curve shows the effect of temperature on the ratio of magnitudes of wear of the guide and slider.

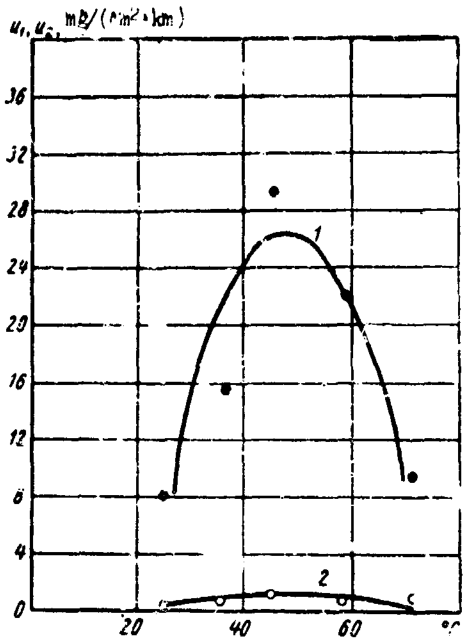


Fig. 26. Dependence of the wear of samples of normalized steels 45 on the temperature of the medium with friction in sea water in contact with the air (S = 24 km, v = 0.66 m/s, p = 3.3 kg/cm^2): 1 - guide; 2 - slider.

The nature of these curves and the distinction of them from similar graphs obtained with friction in deoxygenated sea water can be caused only by the effect of a decrease in the solubility of oxygen in a solution of neutral salts with an increase in temperature. A comparison of Figs. 25 and 26 with Fig. 27 shows that the dependence of the corrosion rate of steel in solutions of neutral salts and the dependence of the intensity of wear of steel in the same medium on temperature are absolutely identical. Results analogous to those depicted on Fig. 27 were also obtained by A. A. Geybovich and his colleagues for corrosion conditions of tube steel in stratified water of the Korobkovsk oil-gas deposits of the Volgograd region, which contains hydrogen sulfide.

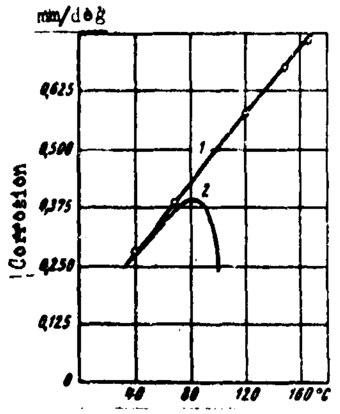


Fig. 27. Dependence of the corrosion rate of iron in water on temperature (after N. D. Tomashov) [84]: 1 - closed system; 2 - open system.

The given data underline the determining value of the corrosion factor in the process of corrosion-mechanical wear of steel with friction in neutral salt solutions and low values of specific pressure.

Effect of concentration of the solution of neutral salts. The chemical composition of the corrosion medium in which the wear of metals and alloys occurs in many respects determines the regularity and intensity of the process.

Investigations of S. L. Naumov showed that independently of the brand of steel and kind of heat treatment, maximum wear is observed in corrosion liquid media with values of pH corresponding to oxidizing acids. When the working media are nonoxidizing acids, neutral salt solutions or alkali, the magnitude of wear is comparatively small [25]. According to data of A. S. Akhmatov, the coefficient of friction of steel on steel increases with an increase in the concentration of the solution NaCl [3]. The dependence of the magnitude of wear of steel 20 and steel 45 on the concentration of the solution is shown in Fig. 20. The character of this dependence is explained by I. V. Vasil'yev by the effect of the concentration of the alkali on the resistance of oxide films forming on rubbing surfaces [5].

Works of P. A. Rebinder, G. I. Yepifanov and N. N. Petrova, and also other authors showed that the presence of surface-active

materials in the working medium can substantially affect the intensity of wear [30].

From Fig. 28 it is clear that the dependence of the intensity of wear of the guide on the concentration of the deoxygenated solution NaCl is close to being linear. The wear of the slider depends little on the concentration of this solution in the absence of the access of oxygen.

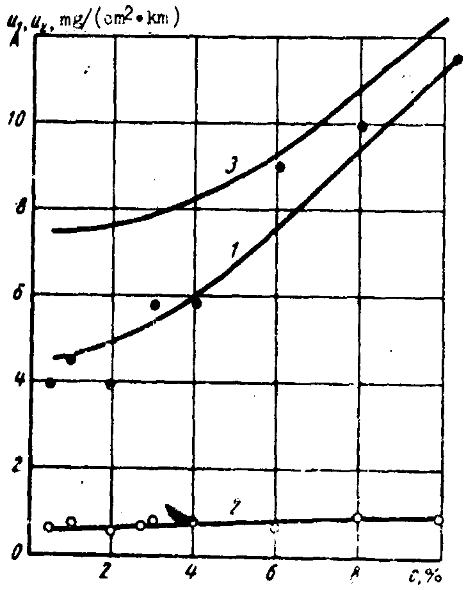


Fig. 28. Dependence of wear of the samples of normalized steels 45 on the concentration of the deoxygenated solution NaCl (S = 24 km, v = 0.66 m/s, p = 3.2 kg/cm^2): 1 - guide, 2 - slider; 3 - ratio of wear of the guide to wear of the slider.

The fact that the shape of curve 1 on Fig. 28 is conditioned namely by the absence of the access of oxygen to the rubbing surface is confirmed by results of another series of experiments, which were conducted under those same conditons but with a free contacting of the working fluid with the atmosphere.

By comparing curve 1 on Fig. 29 with the curves on Fig. 30, which depict results of the investigation of Kh. Ulig [35], it is possible to see their full identity, which indicates the identical dependence of the rate of electrochemical corrosion and intensity of corrosion-mechanical wear of the guide at small values of specific pressure on the concentration of the solution of neutral salt in

which the oxygen is dissolved. The nature of these curves is determined by a decrease in the solubility of oxygen in neutral salt solutions with an increase in their concentration.

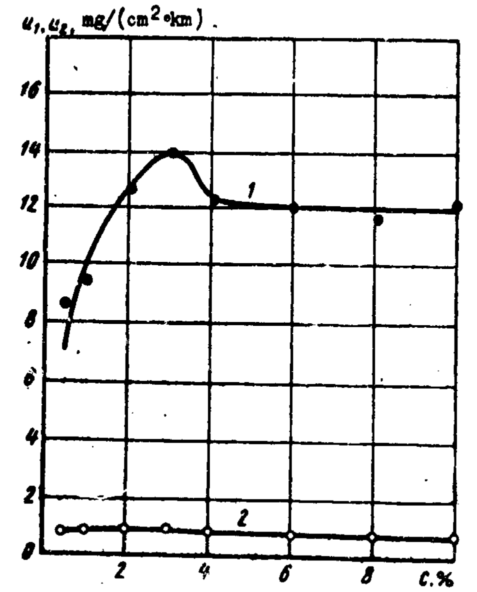


Fig. 29. Dependence of the wear of samples of normalized steels 45 on the concentration of the NaCl solution coming into contact with air (S = 24 km, v = 0.66 m/s, p = 3.2 kg/cm^2): 1 - guide; 2 - slider.

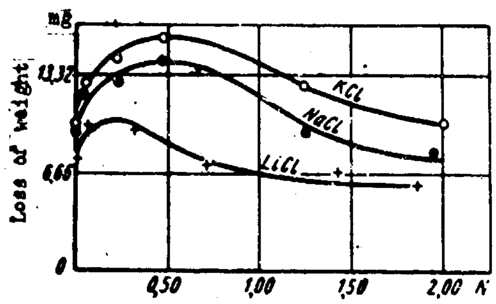


Fig. 30. Dependence of corrosion of low-carbon steels on the concentration of solutions of neutral salts at a temperature of 35°C (after Kh. Ulig) [35].

It seemed to the authors that, just as in experiments conducted by them, the shape of the curve with a maximum (see Fig. 20) is caused by a decrease in the solubility of oxygen with an increase in concentration of the alkali. From source data it is known that the dependence of the solubility of oxygen on the concentration of alkalis and neutral salt solutions is approximately identical.

The effect of other factors on the intensity of corrosion-mechanical wear of steel. The effect of cleanness of the surface of friction on the intensity of the corrosion-mechanical wear of steel was studied by I. V. Vasil'yev. It was established that in a 5% solution of sodium hydroxide the cleanness of the linked rubbing surfaces in the process of wear is determined by the roughness of the surface having a lower class of cleanness. With friction of the metal against nonmetal in 15% sulfuric acid, the cleanness of the surface of the metal is determined by abrasive properties of the nonmetal [6].

In work [6] the effect of the state of strain of the metal of the intensity of corrosion-mechanical wear is also considered. Results of experiments complying with data of A. Ye. D'yachenko [14] showed that the application of tensile stresses to the sample of steel St. 3 changes its resistance to wear with friction in a 5% NaOH solution. In the absence of stresses the wear is maximum, and with tensile stresses of 300-600 kg/cm^2 it is minimum. A further increase in tensile stresses again increases the intensity of wear.

From literature sources it is known that conditions of the removal of products of wear from rubbing surfaces can substantially affect the intensity of the wear of steel in conditions of dry friction and threshold lubrication [19].

Experiments conducted by the authors showed that at an angle of slope of samples to the horizontal plane exceeding 18°, the intensification of their corrosion-mechanical wear is observed. At an angle of slope of 63° the wear of the guide increased by 32% and the wear of the slider by 11% as compared to the wear of samples with their horizontal location in space. The increase in wear of the samples with an increase in the angle of inclination can be explained only by an increase in the fullness of removal of products of wear and a decrease in protective action of the latter.

Results of these experiments give the basis to consider that parts whose rubbing surface are located vertically will be in less favorable conditions of corrosion-mechanical wear as compared to horizontally located rubbing surfaces.

4. One Method of Laboratory Investigation of the Process of Corrosion-Mechanical Wear of Metals and Alloys

From an analysis of the method of formulation and results of laboratory investigations of the process of wear of metals and alloys with friction in corrosion-active liquids, it can be concluded that methods and laboratory equipment used during the study of regularities of wear of the same materials in nonelectrolytes are insufficient for complete elucidation and valid interpretation of the essence of all phenomena accompanying corrosion-mechanical wear.

Let us give the following characteristic example. In experiments of I. V. Vasil'yev, conducted on the machine Kh2-M, the rectilinear dependence of the magnitude of wear of steel 45 from the path of friction established in NaOH solutions with a concentration not exceeding 10%. At higher concentrations of alakali a decrease in the intensity of wear with time was observed. With tests on the machine MI the dependence of volume wear of the same steel on the path of friction had a curvilinear character with all concentrations of alkali from 0 to 20%.

The absence of a direct ratio between the wear of steel 45 and duration of the experiment at high NaOH concentration I. V. Vasil'yev explains by the effect of the concentration of the solution on strength properties of oxide films, which are formed on the rubbing surfaces under the effect of the corrosion medium [5].

Even if one were to agree with such an explanation, the cause of the change of this effect with time remains, nevertheless, vague. Vague also is the cause of the unequal effect of high concentrations of alkali on the wear of steel 20 and steel 45, which possess, as

is known, approximately identical corrosion stability. Without additional special invetigations it is impossible to explain the cause of the different form of graphs wear-path of friction, obtained on machines Kh2-M and MI for the same steels in the same NaOH solutions with a concentration not exceeding 10%.

It is obvious that usual methods of the investigation of processes of wear, including metallographic investigations with the help of contemporary laboratory equipment, cannot completely clear up these and questions similar to them connected with the formation, destruction and reduction primary oxide films on the rubbing surfaces.

In these conditions, considering that the corrosion-mechanical wear constitutes the totality of two simultaneously occurring processes of electrochemical corrosion and mechanical wear, one should consider very important the development of methods which obtaining direct and indirect data about the kinetics and dynamics of electrode processes occurring on the rubbing surfaces in the process of wear.

One of the very promising methods of the study of electrochemical parameters of the process of corrosion-mechanical wear is the measurement of electrode potentials of the rubbing surfaces. This method is based on the comparison of the potential of the rubbing surface, measured in the process of wear, with the potential of this surface liberated from the oxide film, or the so-called dressing potential. The method of determination of the latter, as was shown above, was developed by G. B. Clark and G. V. Akimov and obtained further development in works of N. D. Tomashov and his colleagures [17, 37]. It was established that for the group of metals Al, Cr, Mo and others the dressing potential is displaced to the negative side by 300-1000 mV, for Fe, Ni and Co this shift is 200-500 mV, and for Au, Ag and Cu the dressing potential is almost not changed.

For the first time, as far as we know, the measurement of potentials of rubbing surfaces in the process of corrosion-mechanical wear was carried out by I. V. Vasil'yev. His experiments showed that independently of the concentration of the NaOH solution the intensity of wear of steel 45 in a normalized state increases with a decrease in the difference between values of the dressing potential and friction potential. When this difference approaches zero, catastrophic wear advances [4].

Devoted to the study of electrode potentials of steel 40 with friction against the porcelain disk in solutions with pH variable from 1 to 14 is the work of R. A. Machevskaya and A. V. Turkovskaya. Their experiments showed that in solutions with pH fluctuating from 1 to 5, when the steel is in an active state, the potential of it is not changed with friction and intense mixing of the solution. In electrolytes with pH = 5-10, the potential with friction is equal to the potential with intensive mixing. In solutions with pH variable from 11 to 14, displacement of the potential to a negative side is observed, and this displacement is increased with an increase in pH [24].

Similar experiments conducted by the authors showed that with the friction of steel 45 against steel 45 in a 3% NaCl solution at values of the specific pressure not exceeding 5 kg/cm^2, displacement of the potential of the rubbing surfaces to a negative side is very insignificant. With friction in 0.1 N solution NaOH this displacement reached 500 mV. The latter agrees well with results of work [24].

In conclusion let us note that there is much in this method that is still not clear. However, it is obvious that its further development will allow a deeper study of the mechanism and regularity of corrosion-mechanical wear of metals and alloys.

Thus, laboratory investigations of the mechanism and regularities of mutual wear of constructional unalloyed steels with friction

in solutions of neutral salts showed the following.

1. With slip of the short steel sample (slider) along a sufficiently long sample (guide), which is made of the same material and has the same initial cleanness of the rubbing surface, the intensity of wear of the guide considerably exceeds the intensity of wear of the slider. The ratio of magnitudes of wear of the guide an slider is considerably larger than the ratio observed during wear of the same samples in a chemically inactive medium.

2. Within limits of rates of slip of 0.1-1.0 m/s and specific pressures of 0.5-15.0 kg/cm^2 the presence of two states of the rubbing surfaces and surface layers of the metal is established:

a) at relatively low values of specific pressure (0.5-6.6 kg/cm^2) insufficient for full destruction of the layer of products of corrosion formed on the rubbing surfaces, the nature and intensity of the wear are determined mainly by phenomena of electrochemical corrosion, the effect of which predominates over the action of mechanical factors; in this region neither the rate of slip nor the absolute value of the specific pressure practically affect the intensity of wear;

b) in the region of comparatively high values of specific pressure (above 6.6 kg/cm^2) local destructions of the layer of products of corrosion for the whole depth, the "grasping" of the rubbing surfaces and a sharp rise in the role of mechanical factors in the process of wear are observed; this is expressed, first of all, in the fact that the rate of slip and magnitude of specific pressure substantially affect the intensity of the wear.

3. Starting from a certain moment of time the intensity of the wear of samples remains constant and does not depend on the duration of friction. This moment precedes the period of running-in of the rubbing surfaces the duration of which is longer for the slider than it is for the guide.

4. In the region of relatively low values of specific pressure with a constant hardness of the slider, the wear of the guide depends little on the hardness of it, which is variable depending upon the content of carbon in the steel. An increase in hardness of the slider increases its resistance to wear independently of the magnitude of specific pressure.

5. The presence of oxygen in the working medium sharply increases the wear of the guide and to a lesser degree affects the wear of the slider.

6. The nature of the effect of the concentration of the solution of neutral salts and temperature of the working medium on the mutual wear of steel samples depends on the presence of oxygen in it.

7. Conditions of the removal of products of the wear from rubbing surfaces have a definite effect on the intensity of corrosion-mechanical wear of steel.

C H A P T E R 2

INVESTIGATION OF THE PROCESS OF CORROSION-MECHANICAL WEAR OF EQUIPMENT IN INDUSTRIAL CONDITIONS

1. Description of Industrial Object

The objects for studying the process of corrosion-mechanical wear of steel parts in industrial conditions were certain sections of underground equipment of deep-well-pump installations, which are widely used for pumping oil from oil wells.

A diagram of a deep-well-pump installation is shown on Fig. 31.

The production of the majority of deep-well pumping consists of oil, stratified water and free or dissolved petroleum gas. In a large number of wells together with liquid sand, which is a product of destruction of the petroleum layer, is also taken out. The water quality of production varies over wide limits and can reach 98%. The productivity of the wells is also very diverse from several tens to 250 m^3/days.

The basic cause of corrosion of the equipment of oil wells is the presence of stratified water and corrosive gases in the obtainable production.

Stratified water is a corrosional medium containing in its composition a large quantity of various salts: NaCl, $CaCl_2$, KCl and

others. The effect of the composition of stratified water on the corrosion rate of steel was studied by a number of authors. According to Ts. A. Adzhemyan, in neutral salt solutions at different temperatures and flow rates the corrosion rate of steel, cast iron, nonferrous metals and alloys varies within limits of 0.11-0.22 mm/year. Found in these limits is the corrosion rate of steel in the Caspian Sea water. V. F. Negreyev considers that the conditions of the occurrence of the process affect the corrosion rate to a great degree than does the composition of the water.

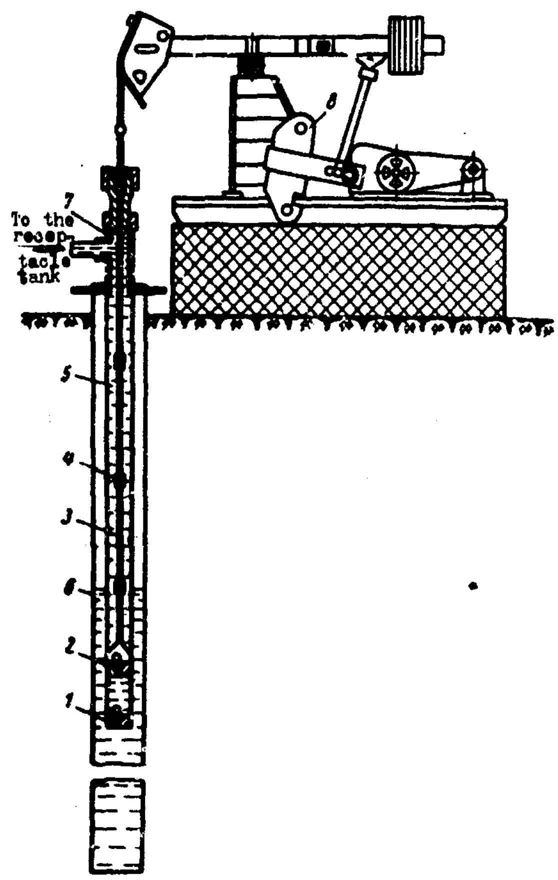


Fig. 31. Diagram of a deep-well-pump installation: 1 - receiving valve of the deep-well-pump; 2 - pressure valve; 3 - pump rods; 4 - rod connecting; 5 - pumping pipes: 6 - siege column; 7 - collar equipment; 8 - pumping jack.

The validity of this point of view is illustrated by results of experiments of A. I. Krasil'shchikov, who showed that in a 3% NaCl solution and in tap water losses of weight in the absence of the access of air are 10-12% of losses observed with the saturation of these liquids by air.

Almost in all works devoted to the corrosion of oil field equipment much attention is given to the effect of different gases dissolved in stratified water and oil.

The hydrocarbon gases themselves are inert. An indirect effect of them is expressed in the fact that they decrease the solubility in water of other corrosive gases.

With a high content of hydrogen sulfide in stratified water point and intercrystalline corrosion of many alloyed steels, especially chrome, is observed. From the point of view of the effect of hydrogen sulfide on the corrosion of metals, there is interest in results of the investigation of V. A. Kuznetsov and E. A. Iof, who showed that with the corrosion steel in the solution of hydrochloric acid the presence of hydrogen sulfide causes the acceleration of both anode and cathode processes; however, the rate of occurrence of the anode processes is increased considerably faster. A similar phenomenon was observed in experiments of V. F. Negreyev [26], who investigated polarization curves of steel in stratified water saturated with hydrogen sulfide.

It has been established by a number of investigations that the presence in stratified water of only carbon dioxide does not considerably affect the corrosion of steel. However, in the presence of hydrogen sulfide, carbon dioxide can considerably accelerate the process. In rigid stratified waters carbon dioxide can indirectly affect the corrosion rate to the side of its increase.

2. Investigation of the Process of Wear of Pumping Pipes and Rod Connecting Couplings

The basic cause of destruction of pump pipes at the Baku fields. The considerable number of stops of deep-pump wells in a number of petroleum regions of the USSR is caused by the unhermeticity of pumping pipes. With appearance of the unhermeticity of pipes the pumped liquid found in their internal cavity will overflow back into shaft of the well, and the feed of it to the surface decreases or is completely ceased (see Fig. 31).

An inspection of a large number of pumping pipes extracted from wells due to the loss of airtightness showed that at the Baku fields where the majority of deep-well-pump installations operating in the USSR is concentrated, the loss most frequently appears due to the abrasion of pipes by rod-connecting couplings. On internal surface of the pipes, as a rule, it is possible to see grooves with a profile corresponding to the profile of the coupling and a length equal to the length of movement of the rods. In most cases ends of the pipes, on the external side of which is a thread, fail. Figure 32 shows the typical form of a pipe with a destroyed end. Such destruction is regular if one were to consider that the thickness of the wall on ends of the pipe is considerably less than the thickness of the wall of the unthreaded part. Furthermore, at high speeds of ascending fluid flow the possibility of erosion of ends of the pipes is not excluded.

An analysis of statistical data showed that in wells supplied with water of more than 60%, where there occurs comparatively rapid wear of deep pumps, the largest number of cases of abrasion of pipes by rod couplings is also observed.

The content of sand in the production of highly watered wells at the Baku fields varies usually in narrow limits - from traces to 0.1-0.3%. It is not possible to establish according to statistical data any quantitative connection between the period of service of pipes and the concentration of sand.

Fig. 32. Typical form of worn-out ends of pumping pipes.

With the inspection of 352 worn-out pipes and 302 worn-out couplings, the following typical forms of rubbing surfaces and state of surface layers of the metal were determined:

1) in wells without water and weakly watered wells, the production of which contains sand, on worn-out part of the internal surface of pipes there are traces of abrasive (Fig. 33). The plastic deformation of surface layers of the metal, as a rule, is not observed;

2) for all pipes extracted from highly watered wells, the rubbing surface is covered by a layer of products of corrosion. The composition of this layer includes in certain relationships different iron oxides (FeO, Fe_2O_3, FeS and others), and also $CaCO_3$ and $MgCO_3$. The content of carbonate of calcium and magnesium does not exceed 5%. In this case two typical cases can be observed:

a) the rubbing surface is covered by a solid layer of products of corrosion, not having noticeable destructions (Fig. 34); surface layers of the metal are not deformed, and the hardness of them does not differ from the hardness of deeper layers; this state is

characteristic for an overwhelming majority of inspected pipes operating in highly watered wells (298 pipes out of 326 operating in 212 wells highly supplied with water);

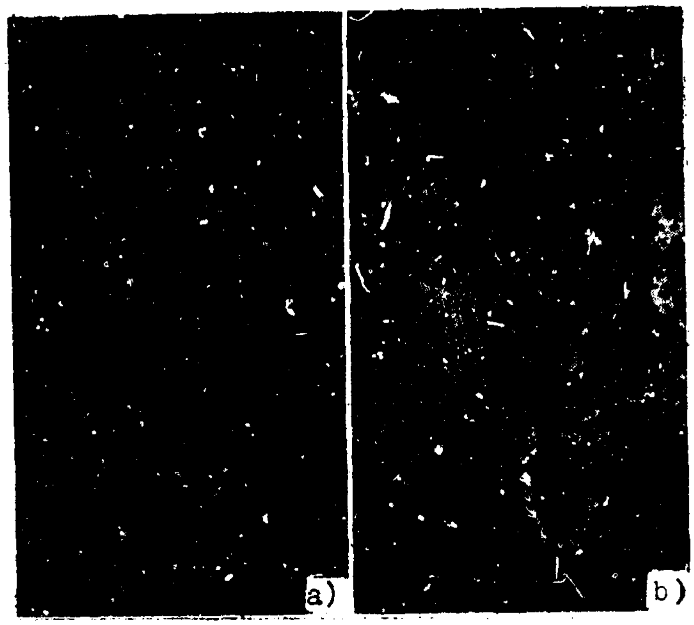


Fig. 33. Photomicrograph of the rubbing surface and microstructure of surface layers of a pipe extracted from a waterless well: a) rubbing surface, ×60; b) microstructure, ×100.

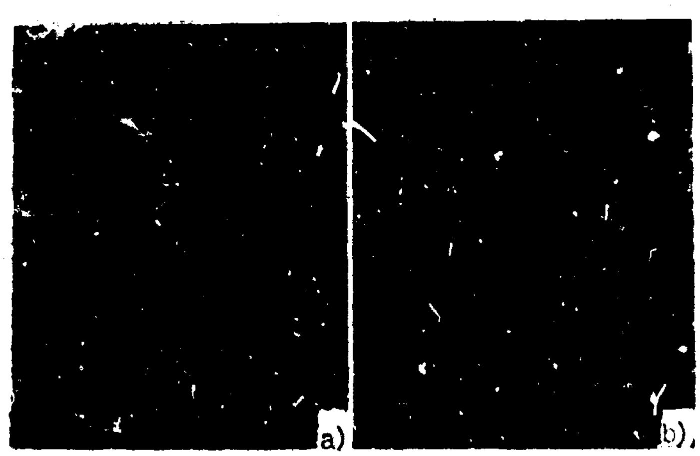


Fig. 34. Typical form of the rubbing surface and microstructure of surface layers of a pipe in highly watered wells: a) rubbing surface, ×60; b) microstructure, ×100.

b) there are large and numerous sections of the destruction of the layer of products of corrosion on rubbing surfaces of the pipes (Fig. 35); surface layers of the metal are plastically deformed; this state of the rubbing surface of pipes is found considerably less often (28 pipes out of 326 extracted from highly watered wells). It is especially characteristic for pipes found in the lower part of the pump.

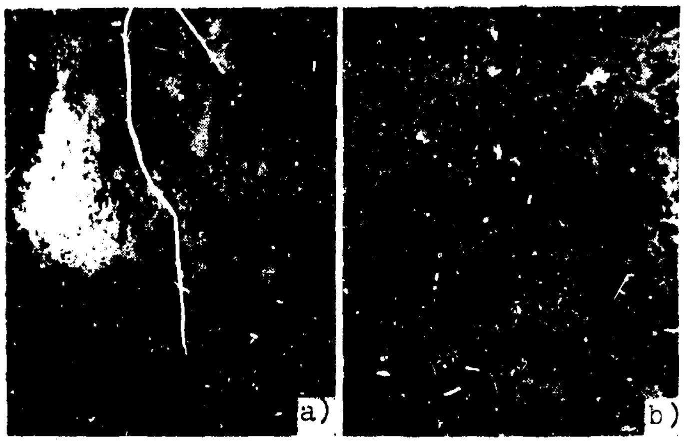


Fig. 35. Photomicrograph of the rubbing surface and microstructure of surface layers of a pipe found in the zone of the longitudinal bend of rods in a highly supplied well.

The rubbing surface of rod couplings in most cases is smooth and shiny. In certain cases on it traces of abrasive are evident.

Plastic deformation of surface layers of metal is rarely encountered.

The nonrubbing part of the internal surface of the pipes and also the surface of the rods in highly watered wells are covered by a solid layer of products of corrosion, the composition of which differs from the composition by the layer available on rubbing surfaces of pumping pipes by a higher content of $CaCO_3$ and $MgCO_3$. The content of these components sometimes reaches 40% by weight.

Method of investigation of the process of wear of the friction pair: pumping pipe and rod-connecting coupling. Experiments were conducted with natural samples of pipes and rod couplings in operational wells. Inasmuch as samples had identical shapes and dimensions, as the criterion of intensity of wear the absolute weight of the worn-out metal was basically accepted. Only in separate especially specified cases other criteria were taken.

The experiments were conducted according to the following method. From ordinary pipes of mass production prepared from steel of one melt and one rolling batch, samples in the form of branch connections 160 mm in length having pipe thread on the ends were prepared. With the help of pipe couplings these samples, preliminarily weighed, were set between two adjacent pipes at the needed point of the column. In certain cases at the same place a few samples, which are united with each other in the form of a unit were set. The place of location of the samples and units coincided with the section of the movement of one of the experimental rod couplings, also weighed before being lowered into the well. After a definite time of operation of the well the samples were extracted and again weighed. Then for obtaining comparative data subsequent batches of samples were set strictly in the same places as the preceding. The internal diameter of the pipes in all experiments was equal to 62 mm (most frequently used pipes in deep-pump operation). The chemical composition and hardness of samples of the pipes and rod couplings, used in all experiments described below, are given in Table 2.

To carry out the experiments, nine wells of oil-fielded administration "Karadagneft'" of the amalgamation "Azneft'," including two experimental (completely supplied with water) were selected. The characteristic of these wells is given in Tables 3 and 4.

Mechanism and certain general regularities of wear of the pair pipe and couplings (TM pairs). From literature numerous attempts are known to represent regularities of the wear of metals and alloys in the form of mathematical formulas, which connect the intensity of wear with load, the physical properties of materials and the medium which wear out the given friction pair.

Table 2. Chemical composition and hardness of natural samples of pipes and rod couplings.

Samples	Brand of steel	All-Union Government Standard	Nominal external diameter in mm	Chemical composition in %							Hardness HB
				C	Mn	Si	P	S	Cr	Ni	
Pipe	45	1050—60	73****	0,43	0,72	0,26	0,25	0,028	0,10	Traces	200
	45*		73****	0,43	0,72	0,26	0,25	0,026	0,10		275
	36G2S	4543—61	73****	0,36	1,46	0,49	0,02	0,025	—	—	229
Coupling	45**	1050—60	46	0,45	0,69	0,31	0,03	0,020	0,09	0,10	212
	45***		46	0,45	0,69	0,31	0,03	0,026	0,09	0,10	50 HRC
	45**		42	0,45	0,67	0,24	0,026	0,03	Traces	Traces	195
	45***		42	0,45	0,67	0,24	0,026	0,03			48—50HRC

*Hardening with tempering.
**Sized rolling.
***Hardening t.v.ch. (high-frequency current).
****Internal diameter, 62 mm.

Table 3. Chemical composition of stratified waters obtained from wells in which the experiments were produced.

Number of well	Deposit	Layer	Equivalent values							Sum of anions and cations	Palmer characteristic			
			Cl	SO_4	HCO_3	naphthenic acids	Ca	Mg	Na+K		S_1	S_2	A	a
339	Lokbatan	VI—VII	0,1281	0,0015	0,0002*	0,0002	0,0101	0,0070	0,1129	0,2600	86,86	12,82	—	0,32
1211	Puta	VIIa	0,0318	0,0018	0,0057	0,0003	0,0005	0,0008	0,0384	0,0794	84,62	—	12,04	3,34
542		VIIa	0,0313	0,0001	0,0074*	0,0003	0,0004	0,0005	0,0393	0,0804	78,13	—	19,62	2,25
1298	Lokbatan	VII	0,0614	0,0007	0,0039	0,0003	0,0006	0,0027	0,0629	0,1328	93,54	-	1,20	5,26
853		IV	0,0550	0,0004	0,0030	0,0002	0,0012	0,0031	0,0543	0,1172	92,66	1,88	—	5,46
895		V	0,0262	—	0,0040	0,0003	0,0007	0,0005	0,0294	0,0612	85,62	—	10,46	3,92
861		IVa	0,0445	—	0,0003	0,0003	0,0004	0,0041	0,0406	0,0902	90,04	8,64	—	1,32
805	Puta	VIIa	0,0280	0,0008	0,0068**	0,0006	0,0007	0,0012	0,0353	0,0744	77,42	—	17,48	5,10

* 0,0010 CO_3.
** 0,0009 CO_3.

Table 4. Technical characteristics of wells in which the experiments were conducted.

Number of well	Average daily yield under normal operating conditions in m^3		Depth of descent of the pump in m	Diameter[1] in mm		Stroke of balancer of the pumping jack in m	Number of double strokes per minute
	oil	water		deep pump	pump rods		
339	—	40	800	43	19	1,8	12
1211	1,0	20	800	43	19	1,8	10
542	1,5	20	800	43	19	1,8	6
1298	2,0	30	650	43	22	2,4—3,0	7,5
853	3,0	60	462	56	22	2,7	11
895	—	30	650	43	22	0,9	16,5
861	1,5	10	650	43	22	1,2	12
806	2.5	30	800	43	19	2,4	7
1187	3,7	—	960	32	19	1,8	7

[1]Pump couplings 62 mm.

Let us consider, for example, one of such formulas derived for conditions of the abrasive wear of steel [19],

$$j_{a\delta} = k\frac{p_H}{HB}, \tag{1}$$

where $j_{a\delta}$ – intensity of abrasive wear; p_H – nominal specific pressure; HB – hardness number of the surface; k – coefficient depending basically due to the type of abrasive.

Formula (1) is accepted for an analysis of results of experiments described below, inasmuch as all wells in which these experiments were conducted gave a production containing a certain quantity of sand. Formulas describing the process of the mutual wear of steel in corrosion liquid media do not exist as yet.

From formula (1) it follows that, other conditions being equal, the intensity of wear decreases with an increase in hardness of the rubbing surface. At identical hardness of conjugate rubbing surfaces one should expect an identical intensity of their wear, especially when the parts are prepared from the same material. However, as was

noted above, such a concept needs reservation, since it does not consider differences in dimensions of rubbing surfaces of mutually wearing parts.

With the stroke of the rods equal to 1.2-3.0 m and the length of the standard rod coupling of 80 mm, the magnitude of the ratio of rubbing friction of the pipe and coupling varies within limits of 15-38. Therefore, in case of abrasive wear one should expect (see Fig. 4), that the intensity of the wear of the pipe will exceed 2-3 times the intensity of wear of the coupling if both elements of the TM pair are made from the same material.

This position is completely confirmed with the wear of the TM pair in noncorrosive media. As one can see from Table 5, the intensity of the wear of the pipes with the pumping out of waterless and sandless oil, waterless oil with sand and tap water without the access of air is approximately three times greater than the intensity of wear of rod couplings. The ratio of magnitudes of wear of pipes and couplings in wells giving stratified water or a mixture of oil with a large quantity of stratified water is completely different. In highly watered wells the intensity of wear of the pipes can exceed tens of times the intensity of wear of couplings with the manufacture of both elements of the TM pair from the same steels 45.

The unequal intensity of the wear of elements of the TM pair can be caused only by a substantial distinction in conditions of wear of the pipe and coupling, which cannot be explained by regularities of abrasive wear described by formula (1).

The rod coupling is in contact with the pipe continuously. With a stroke of the rods of 1.8 m every element of the rubbing surface of the pipe with a length equal to the length of the coupling is in contact with it only 1.06 hours per day, and with a stroke of rods of 3.0 m - only 0.64 hour per day. During the remaining time both the rubbing and nonrubbing parts of the internal surface of the pipe are subjected to the effect of electrochemical corrosion caused by the presence of a large quantity of mineralized water and corrosive gases in the production of the well.

Table 5. Comparison of magnitudes of wear of samples of pipes and rod couplings in experimental wells.

Number of well	Average daily yield during the carrying out of the experiment in m^3		Number of experimental friction pairs	Path of the coupling during the time of the experiment in km	Ratio of stroke of the coupling to the length of the coupling	Average intensity of wear of one sample in gf/m·km		Ratio of intensities of the wear of pipes and couplings
	oil	water				pipe	coupling	
1187	3,7	—	5	3338*	22,4	1,32	0,47	2,80
1298	30,0	—	15	1555*	30,0	0,06	0,02	3,00
1298	—	30,0	15	1555*	30,0	0,76	0,23	3,30
1298	2,0	30,0	9	1555*	30,0	11,60	0,86	13,50
1298	2,0	30,0	9	1555**	30,0	9,04	0,34	29,60
1298	2,0	30,0	9	1555*	30,0	8,90	1,03	8,60
1211	1,0	20,0	15	2253*	22,4	0,95	0,12	2,90
1211	1,0	20,0	9	2715*	22,4	0,97	0,12	8,10
861	1,5	10,0	4	1286*	15,0	3,05	0,44	7,00
339	—	40,0	10	1991*	22,4	1,30	0,11	11,80
542	1,5	20,0	5	2430*	22,4	5,00	0,23	21,60
895	—	30,0	4	1771*	11,2	0,64	0,04	16,10
805	2,5	30,0	5	2124*	30,0	3,54	0,52	6,82
805	2,5	30,0	5	2124***	30,0	3,36	0,13	3,30
853	3,0	60,0	4	1520*	30,0	5,86	0,56	10,50
853	3,0	60,0	4	1520***	30,0	5,86	0,10	8,00

*Soft steel rod couplings.
**The same, steel hardened t.v.ch.
***The same, caprone ($\gamma = 1.1$ gf/cm^3).

Notes: 1. In a well with ratio of intensities of wear of pipes and couplings of 2.80, the sand concentration is 1-1.3%.
2. in a well with a ratio 3.00 there is no sand;
3. in a well with a ratio 3.30 – tap water;
4. in wells with ratios 8.60 and 2.90 – the rod-rotator worked;
5. in wells with ratios 10.50 and 8.00 content H_2S is 400 mg/l.

However, if on the nonrubbing part of the surface of the pipe the protective layer, which consists of products of corrosion and contains a large quantity of carbonates of calcium and magnesium, substantially delays the corrosion rate, then on the rubbing part of the surface of the pipe this layer is continuously removed by the moving coupling. Vertical location of the TM pair in space facilitates the process of dressing.

The cleaned section of the surface of the pipe again intensely corrodes, and products of corrosion again depart with the next stroke of the rods. Such alternating of processes of intense corrosion and removal of products of it continues during the whole period of work of the well between the repair.

Owing to the continuous contact with the pipe, the rubbing part of the surface of the coupling corrodes considerably less as compared to the rubbing part of the surface of the pipe. Therefore, in highly watered wells the ratio of intensities of wear of the pipe and coupling is the same as that during a laboratory test of steel for mutual wear with friction in solutions of neutral salts.

Let us consider the second regularity of wear of the TM pair — the dependence of the intensity of wear on the duration of operation in different categories of wells.

According to formula (1) the intensity of wear, other conditions being equal, is directly proportional to the nominal specific pressure. This dependence, which reflects well the quantitative side of the process of abrasive wear of clean metals, has a somewhat different form during the test of normalized steels. However, in this case the rectilinear dependence of the intensity of wear to specific pressure is retained. Formulas, proposed by other authors, differing in a quantitative respect from formula (1), also indicate that with abrasive wear of steel the intensity of the wear is increased with an increase in specific pressure.

With friction of the rod coupling against the surface of the pipe, both elements of the TM pair wear out, in consequence of which the nominal and real surface of contact are increased. Since here the load pressing the coupling to the pipe remains constant, the specific pressure is continuously lowered. Therefore, assuming that the working medium is constant, and that the wear of the friction pair TM is abrasive, one should expect that the intensity of the wear of pipes and couplings will be continuously decreased with time.

The validity of such an assumption is confirmed by Fig. 36. The experiment was conducted in well No. 1187, which yielded waterless oil with sand.

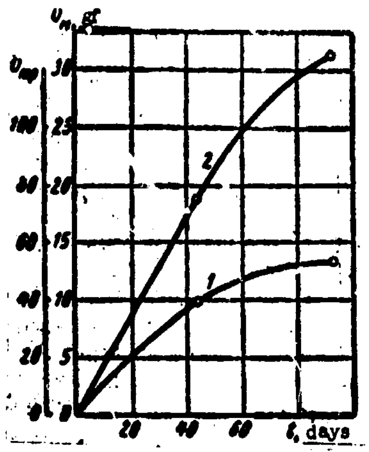


Fig. 36. Dependence of integral weight wear of natural samples of pipes and rod couplings on time in a waterless well No. 1187: 1 - pipe; 2 - rod couplings.

However, analogous experiments in highly watered wells No. 339, 542, 1211, and 1298 gave results opposite to those obtained with the pumping out of waterless oil.

From Fig. 37 it is clear that in all four wells, which are distinguished by their geologic-exploitational characteristic but having a high watered state of production, a growth in the intensity of wear with time is observed.

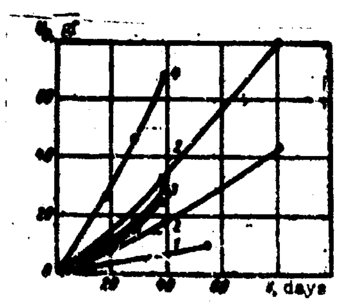


Fig. 37. Dependence of integral weight of wear of natural samples of pipes and rod couplings on time in highly watered wells: 1 - well No. 1211 (pipe); 2 - well No. 542 (upper curve - pipes, lower curve - couplings); 3 - well No. 339 (upper curve - couplings, lower curve - pipes); 4 - well No. 1298 (couplings).

Thus, in highly watered wells, where the shortest period of service of the underground equipment is observed, the regularity of the change in intensity of wear with time differs from that expected by formula (1).

The nature shown on Fig. 37 of buildup of the integral wear of the TM pair in highly watered wells is caused by the following. In the TM pair the initial specific pressure, as a rule, is small. In standard wells it rarely exceeds 5-6 kg/cm^2. The exception is the TM pairs operating in highly bent wells and also in the lower part of the pump in standard wells, where the specific pressure can be considerably increased due to the longitudinal bend of the lower rods [39]. With wear of elements of the pair provoking an increase in the surface of contact, the specific pressure is lowered, since the load remains constant. Therefore, if the wear of the TM pair in highly watered wells would obey laws of abrasive wear, one should have expected that, just as in waterless wells, the intensity of wear will be lowered with time. However, as laboratory investigations described in the preceding chapter showed, in the range of low values of specific pressure the magnitude of the rapid practically does not affect the intensity of mutual wear of steel with friction in solutions of neutral salts. Therefore, in highly watered wells the lowering of specific pressure does not lead to a perceptible decrease in intensity of wear with time.

In these conditions the factors determining the magnitude of integral weight wear of elements of the TM pair and especially the pipe are dimensions of the rubbing surface. The continuous increase in width of this surface with time conditions the form of the dependence of integral weight wear on the duration of friction shown on Fig. 37.

In the practice of deep-well pump exploitation of wells many proposals about the increase in diameter or length of rod couplings are known. Arguments given usually in favor of the increase in overall dimensions of couplings lead to the following. An increase

in diameter of the coupling, other conditions being equal, should extend the period of its service. Furthermore, an increase in diameter or length of the coupling, lowering the specific pressure, should lead to a decrease in wear of the pipes.

The correctness of the first argument is evident. The second argument also would cause no doubt, if the wear of the TM pair were abrasive. However, under conditions corrosion-mechanical wear of the TM pair the usefulness of the increase in dimensions of the couplings causes doubt from the point of view of the possibility of a decrease in wear of the pipes.

Figure 38 gives results of two series of experiments conducted in well No. 895 for studying the effect of dimensions of the coupling on the wear of the pipe. In the first series of experiments the weight of the coupling was increased with an increase in its diameter, and in the second series - with an increase in the length. It is obvious that a cause of the growth in the integral wear with an increase in diameter of the couplings could be only an expansion of the area of contact and absence of a noticeable effect of specific pressure. The growth of wear of the pipes with an increase in length of the coupling, which has a constant diameter, is caused by an increase in the path of friction of the pipe in the absence of the effect of specific pressure.

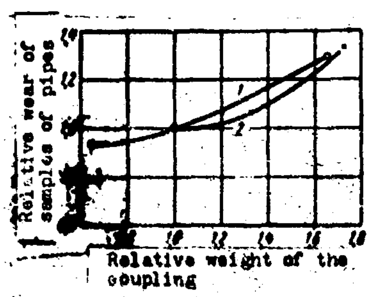


Fig. 38. Dependence of wear of samples of pipes in well No. 339 on overall dimensions of the rod coupling (accepted as unity is wear of the sample of the pipe with friction against the standard coupling from rods with a diameter of 22 mm): 1 - with constant length of the coupling; 2 - with constant diameter of the coupling.

Effect of the medium on the wear of the TM pair. For a more precise definition of the effect of the type of pumped liquid on the wear of the TM pair, several series of experiments were conducted.

An experiment on the study of the effect of the chemical composition of the production of the well was conducted in well No. 1298, where intense wear of the underground equipment was observed.

According to the described method the wear of 15 samples of pipes and 34 soft rod couplings under normal operating conditions of the well was determined (see Table 4). Then the filtering part of the well was covered up to complete cessation of flow from the layer, and the liquid found in the shaft was replaced by pure oil, similar in properties to oil obtained from this well. Under these conditions wear of such a quantity of samples was determined. The well operated on a closed cycle: pipe space - deep pump - pumping pipes - pipe space. The position of the dynamic level remained constant and corresponded to the position of the level in this well under normal conditions of its operation. The third part of the experiment consisted in the fact that the oil found in the well was replaced by tap water, and by the same method the wear of samples is determined during the time accepted in the carrying out of the first two parts of experiment (24 days). During the carrying out of the experiment the pipe space of the well was connected to the vacuum network, and measures excluding the suction of air from the atmosphere were taken.

From Table 6 it is clear that in waterless oil the wear of samples of pipes is 11 times and wear of the rod couplings 12 times less than those in tap water. With operation of the well in normal conditions the wear of the pipes is 8 times and wear of the couplings 1.6 times more than those with friction in tap water. With the pumping out of the waterless oil the wear of the pipes is 85 times and wear of the couplings 19 times less than those under normal operating conditions of the well.

Table 6. Data on the effect of the chemical composition of pumped liquid and aluminum protectors on the wear of samples of pipes and rod couplings in well No. 1298.

Samples	Number of samples	Total wear of samples in gf			
		with pumping out of pure oil	with pumping out of tap water	under normal operating conditions of the well (2 t of oil and 30 m^3 water in days)	under normal operating conditions and in the presence of aluminum protectors
Pipes.....	15	7	76	592	59
Couplings.	34	80	973	1580	839

It is obvious that the considerably greater wear of the pipes during the operation of the well in normal conditions as compared to the wear in tap water, in spite of the complete absence of oil in it, can be caused only by electrochemical corrosion, which is a factor determining the intensity of wear of the TM pair in highly watered wells.

This experiment also showed that the intensification of corrosion properties of the production of the well sharply increases the wear of the pipes and, to a considerably lesser degree, affects the wear of the couplings. The latter agrees completely with results of laboratory experiments described in the preceding chapter.

In connection with the given results of experiment, there is interest in the estimate of losses of metal conditioned by electrochemical corrosion without the combination of it with friction. Such estimate was performed by means of the installation of samples of pipes near samples subjected to wear in such a way that the samples, intended for an estimate of corrosion without friction, did not touch the rod couplings.

From Table 7 it is clear that even in well No. 853, the production of which contains hydrogen sulfide, losses from corrosion without friction are small as compared to losses of metal with corrosion-mechanical wear.

Table 7. Losses of weight of samples of pipes with corrosion without friction in wells No. 1298 and 853.

Number of wells	Number of sample	Distance of sample to the deep-well pump in m	Losses of weight of products of corrosion in g
1298	1 2 3	58 293 575	24 18 14
853	1 2 3	24 182 364	34 22 17

The effect of the type of pumped liquid on the wear of the TM pair is not limited only to the chemical effect of it on the rubbing surface. In petroleum deposits formed similar to the productive stratum of Azerbaidzhan of friable sands, the factor increasing the wear of this pair is the presence of sand in the pumped liquid.

Figure 39 give results of a series of experiments conducted in well No. 339 for studying the effect of sand on the wear of the examined friction pair. A growth in concentration of sand in the pumped liquid from 0 to 0.23% corresponds to an increase in wear of samples of the pipes of approximately 30% and samples in the couplings - 50%. The effect of sand on the wear of the pipes with friction of the soft rod couplings about them proved to be somewhat greater than with the friction of the couplings hardened t.v.ch.

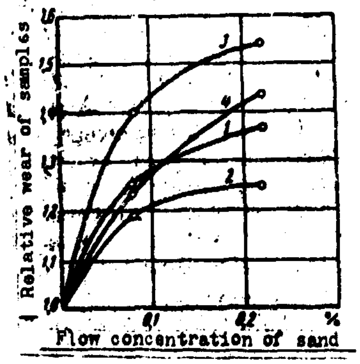


Fig. 39. Dependence of the wear of samples of pipes and rod couplings on the content of sand in water pumped from well No. 339: 1 – wear of pipes with friction agains soft couplings; 2 – wear of pipes with friction against couplings hardened t.v.ch.; 3 – wear of soft couplings; 4 – wear of couplings hardened t.v.ch.

A comparison of results of these experiments with results of experiments conducted in well No. 1298, for studying the influence of the chemical composition of the production of wells shows that the presence of sand in the corrosion medium, although it increases wear of the TM pair, is nevertheless not a factor determining the nature, regularity and intensity of the wear. In highly watered wells, where the flow concentration of sand does not exceed 0.2-0.3%, low periods of service of the pumping pipes are conditioned mainly by the phenomenon of corrosion-mechanical wear.

It is necessary to stress that above the regularities of abrasion of the TM pair, leaving no doubts to the fact that its wear in highly watered wells is chiefly corrosion-mechanical, were obtained in wells whose production did not contain hydrogen sulfide (with the exception of well No. 853). This leads to the very important practical conclusion concerning the fact that the corrosion-mechanical wear of pipes in this category of wells occurs independently of the presence of hydrogen sulfide in them. The presence of hydrogen sulfide in the production of a highly watered well can affect only the intensity of the process of wear and does not determine its character and regularity.

<u>Affect of material and technology of manufacture of pipes and rod couplings on the intensity of wear of the TM pair.</u> In deep-well pump oil extraction basicall pipes of the brand Д, prepared from steel 45, and pipes of the brand E_M, prepared from steel 36G2S (All-Union Government Standard 633-63) are used.

Chemical and mechanical analyses of a large number of samples of pipes used in the Baku fields during the period from 1955 to 1961 showed that the content of the basic chemical elements and mechanical properties, as a rule, vary in permissible limits.

Special experiments conducted in well No. 1298, for which a low period of service of the pumping pipes is characteristic, showed that from the point of view of resistance to wear manganous pipes do not possess perceptible advantages over carbonic pipes: if one were to take the resistance to wear of pipes of mass production of brand Д as unity, then the resistance to wear of pipes of brand $E_м$ is equal 1.05, and the resistance to wear of samples of pipes of brand Д, hardened and tempered up to HB 270-280, is 0.93.

It is necessary to stipulate that although results of the test of samples of hardened pipes agrees well with results of laboratory experiments described in the preceding chapter, the question of the effect of heat treatment on the resistance to wear of pipes needs additional investigation. It is possible that in process of the test hardened samples and soft pipes, among which these samples were determined, formed electrochemical pairs where the hardened steel could serve as the anode. In these conditions considering that the samples were subjected to corrosion-mechanical wear, greater wear of the hardened samples is possible. Therefore, on the basis of results of the above experiment, it is impossible to affirm that heat treatment of pipes is ineffective from the point of view of the resistance to wear of them. To estimate the real effectiveness of heat treatment, the heat-treated samples must be set between pipes subjected to the same treatment. Nevertheless, the experiments conducted give the basis to consider that it is doubtful whether an increase in hardness of the pipes by means of thermal or other kinds of treatment will give positive results from the point of view of an increase in resistance to wear, if in the composition of underground equipment there are sections (for instance, pump rods) which will be able to form corrosion macropairs with the pipes.

Rod-connecting couplings are made from carbon steel, which in chemical composition and hardness is similar to the steel used for the manufacture of pipes of brand Д. At certain plants the external surface of the couplings is subjected to hardening t.v.ch. with subsequent grinding.

The introduction of hardened and ground couplings pursued two goals. An increase in hardness of the coupling should increase its resistance to wear, and an increase in cleanness of its surface should decrease the coefficient of friction in the TM pair and wear of the pipe. These circumstances made a practically interesting setting of special experiments for studying the effect of the material and technology of manufacture of rod couplings on the intensity of wear of the TM pair.

Experiments were conducted in wells No. 1298, 1211, 339, 805, 353, and 861, the geologic-exploitational characteristic of which is given in Tables 3 and 4. Inasmuch as phenomena occurring in well No. 1298 are characteristic for a very great category of highly watered wells, in which, in spite of the absence of hydrogen sulfide, there is observed intense wear of pumping pipes, below results of a series of experiments conducted in this well are given.

Results obtained in the remaining five wells, in which analogous experiments were conducted, were absolutely identical to results obtained in well No. 1298.

Along the length of the column of the pipes three nodes were determined; each of them consisted of two samples of pipes of brand Д and one sample of brand E_M. The distance from the nodes to the deep-well pump was 50.4, 284.7 and 567 m respectively. The diameter of the rods was equal to 22 mm. Except for the effect of a sharp face, available on ends of the couplings, it was preliminarily rounded. Each experiment lasted for 24 days.

From Table 8 it is clear that with friction against hardened rod couplings the total weight wear of samples of the pipes is considerably less than that with friction against couplings not subjected to heat treatment.

Table 8. Data on the effect of the technology of manufacture of rod couplings and the nature of the movement of rods on the wear of samples of pipes in well No. 1298.

Number of node	Distance from node to deep-well pump in m	Wear of samples of pipes in with operation of rod-rotator and friction with		Wear of samples of pipes in gf without rod-rotator with friction with	
		soft couplings	couplings hardened t.v.ch.	soft couplings	couplings hardened t.v.ch.
1	50.4	176	223	293	310
2	284.7	127	102	153	60
3	567.0	125	76	164	94
Total wear of samples		428	401	610	464

Note: In all node on 3 samples each.

The obtained results agrees well with the given laboratory experiments cited in the preceding chapter. From Figs. 9 and 23 it is clear that in the region of low values of specific pressure neither the absolute magnitude of the latter nor the hardness of the slider affect the intensity of wear of guiding, the integral weight wear of which is determined mainly by dimensions of the rubbing surface. Therefore, in industrial conditions, where the sharply differing resistance to wear of the hardened and soft rod couplings conditions the substantial distinction of the width of the rubbing surface, greater integral weight wear of samples of the pipes with friction against soft rod couplings is quite regular.

Calculations not given here due to their cumbersomeness show that between the integral weight wear of samples of pipes and width of the worn out part of the surface of the coupling there is a dependence close to being rectilinear. Thus, for instance, with the resistance to wear of hardened couplings 1.9 times exceeding the resistance to wear of soft couplings (see below), the width of the rubbing surface of the pipe against the soft coupling at every moment of time is 1.26 times more than width of the surface of contact with the coupling hardened t.v.ch.

As can be seen from Table 8, this ratio of magnitudes of rubbing surfaces corresponds ratio of total weight wear equal to approximately 1.3.

Data on the effect of the nature of movement of the rods and technology of manufacture of rod couplings on their wear in well No. 1298 consist in the following.

Wear in % to initial weight is for couplings:

Soft:

with rotation of rods 25.7

without rotation or the rods 19.5

Hardened t.v.ch:

with rotation of rods 13.6

without rotation of rods 10.4

Rotation of wear:

Soft couplings and couplings hardened t.v.ch.:

with rotation of the rods 1.89

without rotation of the rods 1.88

Soft couplings with rotation of rods and soft without rotation of rods 1.32

Couplings hardened t.v.ch. with rotation of rods and couplings hardened t.v.ch. without rotation of the rods 1.31

The fact is characteristic that in case when pumping rods along with the reciprocating rods also accomplish rotation (which is attained with the help of special mechanisms - rod-rotators), the wear of the pipes with friction against soft couplings is approximately the same as that with friction against couplings hardened t.v.ch. (see Table 8). The latter is easily explained by the fact that with the given ratio the resistance to wear of the hardened and soft couplings and rotation of rods, which determines the uniform wear of the couplings over the whole perimeter, the calculation width of the rubbing surface of the pipe against the soft coupling is only 7% larger than the width of the rubbing surface against the coupling hardened t.v.ch.

Very indicative in this respect are results of a test of caprone rod couplings.

It is known that in the search for means of lengthening the period of service of pumping pipes, recently in the USSR and abroad there have been conducted numerous works on the research of nonmetallic materials for manufacture of rod couplings. The theoretical basis of these works is the known position of science about friction, which states that with other conditions being equal the coefficient of friction for heterogeneous materials is less than that for uniform materials. Proceeding from this it is considered evident that if in the TM pair one replaces the metallic surface of the coupling by a nonmetallic surface the coefficient of friction and, consequently, wear of the pipes, will decrease. Even if such replacement leads to a certain lowering of the period of service of the couplings (of course, in permissible limits), it is considered economically justified inasmuch as the pipes are considerably more expensive and more deficient than the couplings. The effectiveness of application of nonmetallic couplings for the lowering of the wear of pipes is considered evident and causes no doubts. Therefore, as far as we know, the study of the intensity of wear of pumping pipes with friction of them against nonmetallic rod couplings has nowhere been conducted.

Judging by source data, materials most frequently proposed for manufacture of nonmetallic couplings are different kinds of oil-stable rubber, caprone, polyethylene, fiber-glass plastic and so on.

In the city of Baku a group of workers of the plant named after L. Shmidt under the leadership of M. L. Sanadze designed the machine which allows pouring on a metallic frame of rod coupling a caprone jacket under high pressure. In reference to rods with a diameter of 22 mm the diameter of the caprone jacket on the coupling is 53 mm, and the length of it is 70 mm (Fig. 40).

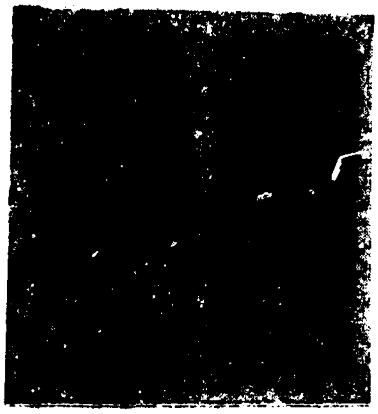


Fig. 40. Rod coupling with caprone jacket.

Tests of caprone couplings were conducted in wells No. 805, 853 and 861. To avoid distortion of results of the comparison of the operation of caprone and metallic couplings, the latter were prepared with the same diameter as that of the caprone jacket and with a length equal to 80 mm.

From Table 9 it is clear that the relative resistance to wear of caprone couplings is not identical in all wells. In well No. 861 the wear of caprone couplings is 3.5 times more than that of metallic, and in well No. 853 the volume of worn-out caprone is only 17% larger than the volume of lost metal. The higher relative resistance to wear of caprone couplings in well No. 853 is caused by the aggressiveness of the pumped liquid, which contains a large quantity of hydrogen sulfide.

Whereas the loss of material by caprone couplings was caused only by the abrasion of them, metallic couplings lost material also due to corrosion without friction. It is necessary to note that in Table 9 the resistance to wear of caprone couplings is compared with the resistance to wear of soft metallic couplings. In the case of the application of hardened metallic couplings the relative resistance to wear of caprone couplings could be considerably lower than that shown in Table 9.

Table 9. Wear of the TM pair with operation of metallic and caprone rod couplings.

Number of well	Number of friction pairs	Average wear in gf of one sample of pipes with friction against		Average wear of one coupling in cm3	
		metallic couplings	caprone couplings	metallic	caprone
805	5	40	38	11,3	21,1
853	4	48	46	8,6	10,1
861	5	62	72	4,5	12,9

However, the most interesting result of the test of caprone couplings is the fact that with friction against them the integral weight wear of samples of the pipes is not less and sometimes greater than the wear with friction against metallic couplings. The latter in practice is important not only from the point of view of an estimate of the efficiency of the industrial application of nonmetallic couplings, but constitutes a graphic illustration of the real nature of the wear of the TM pair in highly watered wells. It shows that the strength of the layer of products of corrosion on the rubbing surface of pipes is so small that the intense wear of it occurs independently of the hardness of the surface of the coupling. As can be seen (see Table 5), the intensity of wear of caprone couplings is considerably less than the intensity of wear of samples of metallic pipes.

Therefore, works on the further increase in resistance to wear of rod couplings should be considered desirable not only from the point of view of the increase in their period of service, but also with respect to the decrease in wear of pumping pipes. In particular, the cementation of rod couplings practiced in the United States, deserves attention; it increases the resistance to wear of them more as compared to hardening t.v.ch. The reinforcing of couplings by belts of hard alloy is also of interest.

Effect of longitudinal bend of lower rods. In the investigation of the dependence of the intensity of wear of the TM pair on the technology of manufacture of rod couplings, it was noted that an increase in their hardness, conditioning the noticeable decrease in wear of the upper part of the column of the pipes, causes at the same time certain undesirable phenomena in the threaded part of the pump.

Thus, for instance, in Table 8 it is interesting that in the lower node, located near the deep-well pump (50.4 m), the wear of the pipes with friction against the soft couplings is less than that with friction against couplings hardened t.v.ch. At the same time in the upper nodes the reverse pattern is observed. Furthermore, as can be seen from the same table, the wear of lower samples of the pipes considerably exceeds in their absolute magnitude the wear of samples sufficiently distant from the deep-well pump. With friction against the soft couplings the wear of three samples in the lower node is 41 48% and with friction against hardened couplings 56-71% of the total wear of nine samples of pipes occurring simultaneously in the test.

The cause of the great wear of the lower samples is easily revealed with their visual inspection and a comparison of them with samples occurring at a great distance from the deep-well pump. Figure 41 shows two simultaneously tested sample of pipes. The first sample was at a distance of 284 m from the deep-well pump, and the second - at distance of 50.4 m. On the first sample there is only one groove, the profile of which corresponds to the profile of the rod coupling.

On the second sample two grooves, the form of which differs from this profile are evident. On certain samples found near the deep-well pump there were three-four grooves each sometimes merging into one wide band. Such a nature of the wear of pipes is caused by the longitudinal bend of the lower rods during a pressure stroke. A definite effect, probably, is felt by the loss in stability of the lower part of the column of pipes during the course of suction [39, 11]. Forces provoking longitudinal bend of the lower rods are friction of the plunger against bushings of the cylinder of the pump, flow friction to the passage of liquid through the pressure valve, and sometimes blows of the plunger against the liquid with an unfilled cylinder.

Fig. 41. Form of internal surface of worn-out samples of pumping pipes extracted from the highly watered well No. 1298: a) outside the zone of longitudinal bend of the rods; b) in the zone of longitudinal bend of the rods.

As a result of the longitudinal bend the rod coupling touches the pipe not at any one section of the internal surface, predetermined by the profile of the well, but at several sections depending upon the form of the axis of the lower rods, which is not identical at every pressure stroke. This leads to a considerable increase in the internal surface of the pipe subjected to intense electrochemical

corrosion with all ensuing consequences. Furthermore, due to the sharp increase in load, which presses the coupling to the pipe with movement of the rods downwards, and the presence of longitudinal bend, the magnitude of the specific pressure can be sufficient for full destruction of the layer of products of corrosion on the rubbing surface of the pipe and the appearance of the phenomenon of "grasping" the rubbing surfaces. Traces of "grasping," not infrequently accompanied by deep-well extraction of metal, are distinctly evident on one of the lower samples of the pipes tested in highly watered well No. 1211 (Fig. 42). In these conditions, as laboratory experiments showed, at high values of specific pressure an increase in hardness of the slider causes a very perceptible intensification of wear of the guide (see Fig. 24). Therefore, the wear of lower pipes with friction against the hardened couplings is greater than that with friction against soft couplings.

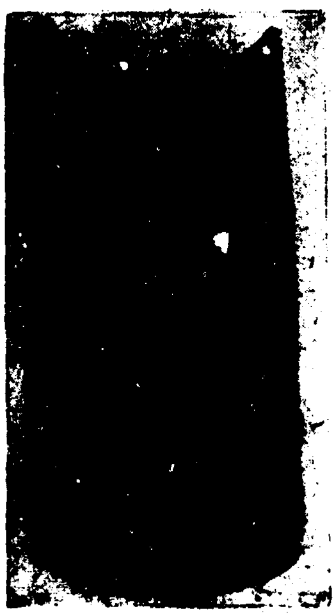


Fig. 42. Traces of deep-well extraction of metal on a pipe located in a zone of longitudinal bend of rods in a highly watered well.

Practice shows that the wear of lower pipes is determined not only by the magnitude of forces causing longitudinal bend of the rods, but also by the design of the lower part of underground equipment of

the well. The greater the diameter of the pipes and the smaller the diameter of the rods, the more favorable the conditions for the appearance of the longitudinal bend and the more perceptible its negative consequences.

In connection with this one should note that the standard designs of columns of rods used are unprofitable from the point of view of the wear of lower pipes. In wells exploited by pumps with a diameter of 28-44 mm, which constitute the majority of deep-well pump wells at Baku fields, the lower rods, as a rule, have diameter, of 19 or 16 mm. Even with small loads concentrated at the plunger of the pump, these rods easily lose the stability with all ensuing consequences. Breaking down especially often are the lower pipes in wells, exploited by insertable pumps with a diameter of 43 mm, with diameters of the pipes and rods equal, respectively, to 62 and 19 mm.

Table 10 gives results of experiments conducted in well No. 1211. The design of the underground equipment of this well differed from that accepted in well No. 1298 (see Table 4) only by the fact that the diameter of the rods was decreased from 22 down to 19 mm. Thus, just as in well No. 1298, the faces on ends of the couplings were rounded.

Table 10. Data on the effect of the technology of manufacture of rod couplings and longitudinal bend of rods on the wear of samples of pipes in well No. 1211.

Distance from samples of pipes to deep-well pump in m	Quantity of samples in the node	Total wear of samples of pipes in the node in gf with friction against couplings	
		soft	hardened t.v.ch.
23.4	3	75	262
242.7	2	49	8
356.6	4	47	31
397.6	4	54	49
Total wear of all samples		225	350

With a comparison of Tables 8 and 10 it is possible to see the noncorrespondence of results of experiments consisting in the fact that in well No. 1298 the total wear of samples of the pipes was greater with friction against the soft rod couplings, and in well No. 1211 – with friction against couplings hardened t.v.ch.

However, this is only an apparent noncorrespondence. With the operation of soft couplings in well No. 1211 from 225 gf of metal lost by all 13 samples of pipes, only 70 gf, or 33%, belonged to the portion of the lower three samples. With the operation of couplings hardened t.v.ch., in this well of the total loss of weight of samples of the pipes equal to 350 gf, 262 gf, or 75%, are lost by three samples found at a distance of 23.8 m from the deep-well pump. For samples of pipes sufficiently distant from the pump, the wear of the pipes with friction against hardened couplings also, just as in well No. 1298, is less than that with friction against the soft couplings. Thus, the sharp growth in the total wear of samples of pipes in well No. 1211 with friction against the hardened couplings occurred exclusively due to the increase in wear of the lower samples owing to the longitudinal bend of the rods, which was intensified due to the unfavorable design of the rod column.

3. The Wear of a Plunger Pair of a Deep-Well Pump

Deep-well pumps are used for pumping out liquid from oil wells. A diagram of an uninsertable deep-well pump[1] is shown in Fig. 43. The cylinder is made in the form of a set of bushings with a length of 300 mm each with a diameter fluctuating within 28-95 mm. The number of bushings in the pumps of contemporary manufacture made in

[1]Pumps of insertable design are also used, and they distinguished by the fact that with an identical internal diameter of the bushings the external (dimensional) diameter of the bushings is less than that for pumps of uninsertable design. In contrast to uninsertable pumps the cylinder and plunger of insertable pumps descend together into the well on rods and do not require the extraction of pipes from the well in the replacement of the pump.

the USSR has been changed from two to seventeen. Depending upon conditions of operation bushings from cast iron, steel 45, hardened t.v.ch., and nitrated steel 38KhMYuA are used. The hollow steel plunger has a standard length of 1200 mm and a chrome-plated, polished surface. The magnitude of the radial clearance on the diameter between bushings of the cylinder and plunger varies depending upon the class of the fitting within 20-180 μ.

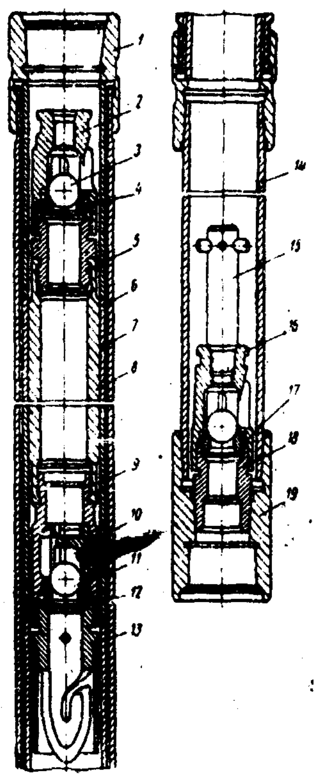


Fig. 43. Deep-well rod pump: 1 – coupling of the cylinder; 2 – valve cage; 3 – ball; 4 – valve seat; 5 – nipple of plunger; 6 – bushing; 7 – housing; 8 – smooth plunger; 9 – housing of valve; 10 – valve sleeve; 11 – ball; 12 – valve seat; 13 – catcher; 14 – pipe-extension; 15 – rod-catcher; 16 – valve cage; 17 – valve seat; 18 – tip cone; 19 – cone seat.

Below results are given of certain experiments illustrating the effect of the working medium on the wear of the plunger pair of the deep-well pump. The effect of other factors is not considered here, and this is evident in greater detail in works [29,1].

On deposits formed from weakly cemented sands, the basic, although not the only, factor determining the period of service of deep-well pumps is the abrasive action of the sand contained in the pumped

liquid. Representation on the effect of sand on the wear of the plunger pair of the deep-well pump is given by results of an experiment conducted by authors in the completely watered well No. 339, the characteristic of which is given in Chapter 2 (see Tables 3 and 4). An experiment was conducted with two identical deep-well pumps of the 1st class of fitting. The internal diameter of bushings prepared from nitrated steels 38KhMYuA was equal to 43 mm. With a stroke length of the pumping jack equal to 1800 mm and 12 oscillations of the balancer per minute, the theoretical productivity of the pumps was equal to 50 m^3/days.

The experiment consisted of two parts. In the first part almost all the liquid fed to the surface by one of these pumps lowered to a depth of 800 m headed back into the well, i.e., circulation of the liquid was conducted according to the scheme: well-deep-well pump-pump pipes-measurement device-well. The whole system was hermetically sealed and connected to the vacuum pipeline. Inasmuch as with the operation by this scheme liquid from well was almost not removed, sand was absent in the circulating liquid. Upon the expiration of time sufficient for obtaining representation about the nature and intensity of wear of the pump, the second part of the experiment was conducted. The pump was taken from well and replaced by a second pump. All other sections of the installation and parameters of its operation remained constant. The difference consisted only in the fact that in the second part of the experiment all the liquid fed to the surface was removed from the well owing to which the flow concentration of the sand was increased to 0.25-0.36%. Due to the fact that the well had a very high coefficient of productivity, the difference between positions of dynamic levels in the first and second parts of the experiment did not exceed 30 m. Therefore, it is possible with negligible error to consider that the pressure drop on ends of the plunger was identical in both parts of the experiment.

Accepted as criterion of the estimate of the rate of wear of the deep-well pump was the change in its actual productivity with time. The permissibility of the use of this criterion was conditioned by

the fact that with the rise in the operating pumps complete airtightness of the valve junctions was fixed. This gives the basis to consider that the decrease in supply of the pump with time was caused by only the wear of its plunger pair.

According to work [29] the connection between current productivity of the deep-well pump and the time of its operation is described by equation

$$q = q_н - at^m, \tag{2}$$

where q — current productivity; q_H — initial productivity; t — time the pump operated; a — proportionality factor dependent on quality of the pump, its design, parameters of operation of the installation and type of liquid pumped out; m — exponent characterizing the rate of wear of the plunger pair.

From Fig. 44 it is clear that both in the absence of sand in the pumped liquid and with the flow concentration of the sand equal on the average to 0.3% and very frequently encountered at the Baku fields, the magnitude of the exponent m is approximately identical. A sharper drop in the productivity of the pump with time in the presence of sand in the pumped liquid, as compared to the lowering observed with the pumping out of the sandless liquid, occurred due to the substantial growth in the proportionality factor a in equation (2).

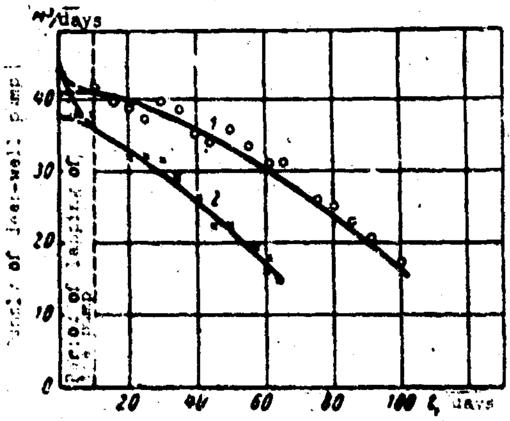


Fig. 44. Dependence of the productivity of the deep-well pump on the duration of its operation during the pumping out of stratified water from well No. 339: 1 — in the absence of sand $q = 41.7 - 0.019\ \tau^{1.55}$ m³/day; 2 — with flow concentration of sand 0.25-0.36%, $q = 38 - 0.12^{1.26}$ m³/day (in the calculations the time reading is started from $t_1 = 10$ days).

As can be seen from Fig. 44, the influence of sand is especially great at the initial period of operation of the pump. The latter is regular inasmuch as the abrasive action of the sand should appear stronger, less the gap between the plunger and the cylinder, i.e., in the period of running-in of the plunger pair of the pump. Consequently, the effect of sand on the wear of this pair is represented by a diminishing time function. The transform of the productivity of the deep-well pump in the form of a monomial exponential function contains a known element of conventionality, since it does not consider the very high intensity of wear in the period of running-in of elements of the pair, especially with the pumping out of the liquid with the sand.

The practice of exploitation of deep-well pump wells shows that the intense wear of deep-well pump can be observed in the absence of an abrasive in the production. One of the most important factors determining the rate of the plunger pair in sandless wells are corrosion properties of the pumped liquid.

The effect of corrosion agents can be judged according to results of the experiment described below, carried out jointly with M. S. Rustamov [31]. Into one of the idle wells, after the sealing of holes connecting the shaft of the well with layer, at a depth of 730 m a pump of the 1st class of fitting with bushings made of superficially hardened steels 45 and an internal diameter of 43 mm was lowered. The stroke length of the pumping jack was equal to 900 mm, and the number of pumpings of the balancer was 14.1 per minute. The theoretical productivity of the pump was 24.7 m^3/days. The working medium was Caspian Sea water without an abrasive. The liquid fed by the deep-well pump headed into the open capacity and from there through flow gauge back into the well. Thus, the column of the liquid under the pump with a height of 30 m remained constant for the period of the whole experiment, which lasted for 100 days. After termination of the experiment the airtightness of valve nodes of the pump was checked, and it was established that the productivity decreased with time only due to wear of the plunger pair.

Results of this experiment are shown in Fig. 45 (curve 1). Curve 2 is plotted from data of the second experiment conducted according to the same scheme as that of the pump, which had an accurate characteristic, just as in the first experiment, but with strict hermetic sealing of the whole system. The pipe space of the well was joined to the vacuum pipeline. As can be seen from Fig. 45 (curve 2), the value of the exponent m was decreased approximately twice.

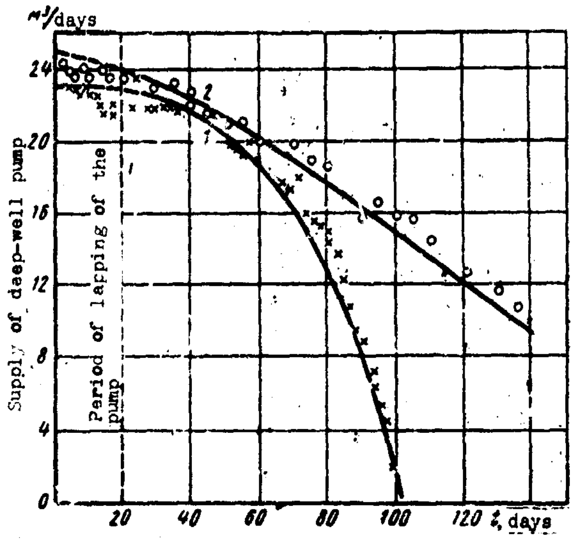


Fig. 45. Dependence of productivity of the deep-well pump due to the duration of its operation with the pumping out of sea water from the well with a flooded end face: 1 – with access of air $q = 23-8511 \cdot 10^{-9}\ \tau^{3.17}$ m^3/day; 2 – without access of air $q = 24-0.01\ \tau^{1.48}$ m^3 day. (with calculations the time reading is started from $t_1 = 20$ days).

It is obvious that such an intense wear of the deep-well pump in the first experiment was caused by the fact that circulating sea water, passing through the open capacity, seized the air, causing an intense corrosion of not only the rubbing surface, but also all underground equipment with the exception of valves made of stainless steel.

It is obvious that such a strong effect of oxygen on the wear of the deep-well pump in the first experiment was caused also by the fact that in the circulating liquid oil was absent. In real conditions of exploitation, when the pumped liquid constitutes a mixture of oil, stratified water and gas, the action of corrosion will be delayed owing to lubricating properties of the oil. According to A. P. Gasanov, the effect of the quantity of water contained in the pumped liquid appears only when this water sufficiently corrosion-active [9, 10]. These works of A. P. Gasanov confirm the earlier expressed assumption about the fact that in highly watered wells, where even in the absence of sand a low period of service of all sections of the underground deep-well pump equipment is observed, the intense wear of it is caused not so much by the great magnitude of the coefficient of friction as the aggressiveness of the working medium [21].

Thus, experiments conducted with natural samples of pipes and couplings in industrial conditions showed that:

1. In highly watered wells, where the low period of service of the deep-well pump underground equipment is observed, the process of wear of the pump pipes, which occurs chiefly at low values of specific pressure, is controlled by electrochemical corrosion, caused by the presence of mineralized water and aggressive gases in the pumped-out production.

2. Corrosion-mechanical wear of pump pipes in highly watered deep-well pump wells occurs independently of the presence of hydrogen sulfide. Hydrogen sulfide substantially increases the intensity of the corrosion-mechanical wear of the pipes but does not determine the nature and regularity of the process.

3. The presence of sand in the production of the highly watered deep-well pump well, although it intensifies the wear of the pipes, is not a factor determining the nature and regularity of the process of wear.

4. The longitudinal bend of the rods sharply increases the intensity of the wear of the pump pipes in highly watered wells, especially in the case of the application of hardened rod couplings.

CHAPTER 3

ON THE EFFECTIVENESS OF DIFFERENT METHODS OF COMBATTING THE CORROSION-MECHANICAL WEAR OF THE EQUIPMENT

Laboratory investigations and industrial experiments, carried out at a different time for the search of effective means of decreasing the wear of metals with friction in corrosive liquid media, were conducted basically in two directions: estimates of the effectiveness of the application of metals resisting corrosion in different operating conditions, and uses of electrochemical protection and inhibitors of corrosion for decreasing the corrosion-mechanical wear of parts prepared from the standard undeficient metals and alloys.

In selecting materials for friction of pairs operating in solutions of sulfuric acid, I. V. Vasil'yev and A. P. Kireyev came to the conclusion that the corrosion stability of metals in given conditions has a greater effect on the process of wear than do other properties, as, for instance, hardness, capacity for work hardening and so on. It is established also that the usual corrosion tests, conducted at the operating temperature of the medium, can characterize the behavior of the metal with friction in this medium only in the case when the corrosion stability of it is changed insignificantly with a change in temperature [7]. M. Fater, who conducted laboratory experiments on the wear of alloyed and unalloyed steels with a stream of water, also came to conclusion that the resistance to wear of these materials is determined more by the corrosion stability than mechanical strength.

The little effectiveness of the increase in mechanical characteristics of rubbing surfaces of parts subjected to wear in solutions of neutral salts is also indicted by results of the experiment conducted by authors with samples of pumping pipes in watered oil wells. The internal surface of samples made of steel 45 was nitrated, as a result of which the hardness of it was increased up to 80 units on scale A. The samples were placed between the pumping pipes on sections of the movement of soft rod couplings.

Figure 46 shows such a sample after 24 days of its stay in well No. 1298, the characteristic of which is given in Chapter 2 (see Tables 3 and 4). It is obvious that in operating conditions, which cause such a small resistance to wear of the nitrated surface, the practically realizable measures on the improvement of mechanical characteristics of metallic pumping pipes will hardly be able to increase noticeably the resistance to wear of them.

Fig. 46. Sample of a pipe of steel 45 with nitrated internal surface after a stay of 24 days in well No. 1298.

It is necessary to note that in the practice of the operation of machine parts such rigid conditions of wear can be observed that even for especially corrosion-stable alloys having an oxidized film which is the thinnest and most durably connected with the metal, nevertheless, destruction of the film with friction occurs. It is known also that stainless steels, although to a lesser degree than carbon, are subjected to destruction due to cavitation. Experiments conducted by authors with samples of pumping pipes made of steel 3Kh13 showed that the resistance to wear of this steel in rigid operating conditions is insufficiently high, although it is higher than that for nitrated steels 45.

The conducted experiments, and also a number of other works, permit concluding that although the corrosion-mechanical wear in rigid conditions of friction can be decreased by the application of corrosion-stable steels, the effectiveness of the use of these materials is limited. Therefore, the application of them for the manufacture of parts subjected to intense corrosion-mechanical wear cannot be considered in a large number of cases as a radical solution to the problem.

When corrosion-mechanical wear is subjected to a huge number of such metal-consuming articles as pumping pipes, the question of the application of stainless steels, in general, drops out due to the high costs and deficiency of these materials.

The importance of works on the search of materials possessing satisfactory resistance to wear with friction in corrosive liquid media is sufficiently great. However, a substantial increase in the longevity of equipment subjected to corrosion-mechanical wear can be attained mainly by means of an operating nature. These works should include, first of all, measures on the effect of the nature of the process of wear.

There is no doubt that in the presence of means of the transformation of corrosion-mechanical wear of machine parts into simple mechanical wear, the period of service of these parts would be substantially increased. Such a transformation is possible only in the case of complete exclusion or considerable weakening of the effect of corrosion phenomena on the process of wear.

The search for effective means of fighting corrosion, which in practice are applicable for the protection of mobile parts, should be at present considered as the basic goal of works in the field of increasing of the longevity of equipment subjected corrosion-mechanical wear.

Above it was indicated that works conducted by different authors in this direction, concerned mainly two aspects of the protection of metals from electrochemical corrosion: electrochemical protection and corrosion inhibitors.

The theoretical foundation of the application of electrochemical protection as a means of fighting the wear of parts in electrolytes is given by N. D. Tomashov in the work [36].

In the opinion of many authors, this protection is simpler and more convenient to accomplish in practical conditions with the help of protectors. Metals utilized usually as protectors are magnesium, aluminum, zinc and their alloys.

An illustration of the effectiveness of this form of electrochemical protection can be results of experiments of N. D. Tomashov and V. G. Sapozhnikova, who tested for corrosion-mechanical wear of the neck of standard fatigue samples in the presence and absence of zinc protectors. With the installation of a zinc protector the wear of samples with friction in neutral salt solution decreased 6-9 times as compared to wear observed during a test without a protector [36]. The other example of the high effectiveness of this kind of electrochemical protection is given in the work of W. Hillis and V. Mackenzie, who achieved a sharp decrease in wear of equipment of the woodworking industry with the help of protectors [48]. Good results were attained by S. Rosenberg and L. Jordan, who used the protector protection to decrease the wear of steel with friction of it against textolite in sea water. The theoretical basis of questions of the protector protection of steel from corrosion in stratified waters is given in work [12].

It is established by experiments that from the point of view of current yield and protective properties, magnesium and its special alloys possess considerable advantages over zinc and aluminum. However, in view of the great activity of magnesium, the period of service of protectors made from it is considerably lower than that of protectors from alloys of aluminum and zinc.

An investigation of the possibility and expediency of the application of protectors as a means of preventing corrosion-mechanical wear of parts of petroleum equipment was conducted by the authors by the formulation of special laboratory and industrial experiments. The laboratory experiments were conducted on a test stand according to the method described in Chapter 1.

The working medium was deoxygenated sea water, which had a temperature of 25°C and moved in the cavity of the stand at a rate of $6 \cdot 10^{-5}$ m/s. The protectors were plates of zinc and aluminum with a weight of 80 gf, which came into contact with the motionless sample. The duration of each experiment was 10 hours, during which the slider accomplished a path of friction equal to 24 km at a speed of 0.66 m/s. The experiments were conducted at nominal values of specific pressure equal to 3.4 and 13.5 kgf/cm^2. Each friction pair was preliminarily run-in for 10 hours without a protector.

From Table 11 it is clear that at a specific pressure of 3.4 kgf/cm^2 the ear of the guide with a zinc protector decreased 8 times and the wear of the slider 2.8 times as compared to the wear during a test without a protector. An aluminum protector was considerably more effective. With it the wear of the guide decreased approximately 14 times, and the wear of the slider – 3.1 times.

Table 11. Data on the effect of protector protection on the intensity of mutual wear of samples of normalized steels 45 with friction in deoxygenated sea water.

Number of experiment	Protector	Specific pressure in kgf/cm^2	Intensity of wear in mgf/cm^2·km		Ratio of magnitudes of wear of the guide and slider
			slider	guide	
1	Without a protector......	3,3	0,58	3,71	6,40
2	Zinc....................	3,3	0,21	0,46	2,19
3	Aluminum................	3,3	0,19	0,27	1,44
4	Without a protector......	13,5	2,93	12,20	4,15
5	Aluminum................	13,5	1,96	6.03	3,08

During the analysis of data given in Table 11, it is to be noted that at a specific pressure of 3.4 kgf/cm^2 the wear of the guide in the presence of protectors decreased to a considerably greater degree than the wear of the slider. In this case if the degree of the decrease in wear of the guide greatly depends on the kind of protector, then the wear of the slider is approximately identical both in the presence of zinc and aluminum protectors. These data can serve as a confirmation of an earlier made conclusion concerning the fact that with mutual corrosion-mechanical wear of steel the factor of corrosion has a considerable effect on the wear of the guide and to a much smaller degree affects the wear of the guide.

Proving less effective was protector protection in conditions of mutual corrosion-mechanical wear at comparatively high values of specific pressure.

From Table 11 it is clear that at a specific pressure of 13.5 kgf/cm^2 the wear of the guide in the presence of an aluminum protector was reduced a total of 2.3 times and the wear of the slider 1.5 times. The latter is quite regular if one were to consider that at values of specific pressure sufficient for complete destruction of the layer of products of corrosion on the rubbing surface of the guide the role of the mechanical factor in the process of wear sharply increases, and the relative effect of corrosion phenomena decreases.

In industrial conditions one of the varieties of electrochemical protection — cathode polarization from an external source of current — found a certain application for protection from corrosion of the external surface of casing columns of oil wells However, such a form of protection of rubbing parts of petroleum equipment can hardly find industrial application due to the complexity of the design solution to a problem.

A first attempt to estimate the effectiveness of protector protection as a means of decreasing the wear of the pumping elevator of pipes was conducted by authors in well No. 1298, the characteristic of which is given in Tables 3 and 4. Used as a protector was an

aluminum wire, reeled on the funnel of the rod, which moved opposite especially fixed samples of pipes (for the method of carrying out the experiments see Section 1, Chapter 2). The weight of each protector was equal to 200 gf [21].

From Table 6 it is clear that under normal operating conditions of the well the wear of samples of pipes in presence of protectors decreased 10 times, and wear of couplings decreased approximately 2 times as compared to the wear observed in the same operating conditions but without protectors. In spite of the fact that used as a protector was almost pure aluminum, and not a special aluminum alloy protector, it almost completely eliminated the factor of corrosion from the process of wear, turning corrosion-mechanical wear into simple mechanical wear. This is indicated in the approximately identical magnitude of wear of samples of pipes in the case of normal operating conditions in the presence of protectors and with the pumping out of tap water without the access of air.

Thus, results of the experiment conducted in operating conditions, which agree well with results of laboratory experiments, confirmed the fundamental possibility of a sharp decrease in wear of pumping pipes by the usual means protection from corrosion.

However, with attempts of the industrial application of protector protection for decreasing the wear of pipes difficulties were encountered.

It is obvious that in industrial conditions the installation of protectors on each pipe or rod is impossible. Protectors in the form of separate masses, placed along the axis of the pump, can find industrial application only in the case when the range of operation of each of these masses will be sufficiently large and the protector itself long-lasting. Therefore, from the point of view of the application of protectors for decreasing the corrosion-mechanical wear of the pipes, questions of the range of operation of the protector and the longevity of it are paramount importance.

Experiments carried out by authors for investigating this question were conducted in wells, Nos. 805, 853 and 861.

In well No. 861 an experiment was conducted with one protector with a weight at 360 gf. Thus, just as in well No. 1298, the aluminum wire applied as the protector was reeled on the funnel of the rod moving opposite one of the samples of the pipes. The remaining three samples of pipes, opposite which the protectors were not installed, were at distances equal, respectively, to 34, 64 and 72 m from the site of installation of the protector. The duration of the experiment was 40 days. Accepted as a criterion of effectiveness of the protector was the ratio of the magnitude of wear of samples of pipes in the absence of protector to the magnitude of wear with a protector.

From Fig. 47 it is clear that just as in well No. 1298, the wear of the sample of the pipe at the place of installation of the protector decreased 10 times. However, with distance from the place of installation of the protector, the effectiveness of it is rapidly reduced and at a distance of approximately 40 m the action of the protector is no longer entirely felt. Such a characteristic of an aluminum protector cannot be considered satisfactory, even if one were to assume that the application of special alloys on the aluminum base will slightly increase the range of operation of it.

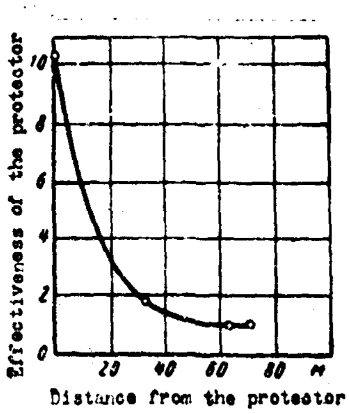


Fig. 47. Dependence of effectiveness of an aluminum protector on the distance to the place of its installation in well No. 861.

Proceeding from the obtained results, with the setting of similar experiments in wells Nos. 805 and 853, a special magnesium protector alloy (magnesium content, 91%) was used. A protector with a weight of 3.1 kgf was installed on pipes with the help of special housings. The duration of the experiment was 40 days.

Results of the experiments showed that the effectiveness of magnesium protectors is considerably lower than aluminum ones. Directly at places of installation of the protectors the wear of samples of the pipes decreased 3-5 times, and at a distance of 15-20 m the action of the protector was not totally felt. In checking the state of the protectors after a stay of 40 days in wells, it was found that the housings were empty and the protector alloy was absent. There is basis to consider that the protector was dissolved during a very short time interval, and during the remaining part of the interrepair period of operation of the wells wear occurred with the same intensity as without the protector. A magnesium protector with the same weight, installed on the ground pipeline connecting well No. 805 with the reservoir, was dissolved in [illegible] s in spite of the absence of hydrogen sulfide in the productio[illegible] f [illegible] well.

Thus, the experiments above described showed that it is doubtful whether the concentrated protectors will be able to find wide application as means for decreasing the corrosion-mechanical wear of underground deep-well pump equipment of oil wells. However, there is no basis to consider the protector protection of this equipment as being hopeless. Subsequently, probably, rational forms of the realization of this in a fundamental respect of a very effective method can be fou[illegible]d. Such forms, possibly, will be the thermal diffusion zincing of rods and the internal surface of the pipes or covering of these surfaces by special protector compositions.

Let us consider results of certain works on the application of corrosion inhibitors for decreasing the corrosion-mechanical wear of the equipment of oil wells.

Corrosion inhibitors are surface-active materials, which, being absorbed on the surface of steel, form protective adsorptive films on it. The hydrophobic nature of the surface occurring here improves the wetting of it by the oil and retards the development of corrosion processes [27]. As inhibitors of corrosion organic substances with great molecular weight and popular connection are usually used.

Positive results were obtained in the use of corrosion inhibitors for decreasing the corrosion-mechanical wear of steel in laboratory conditions. In work [15] results of experiments are given showing that with the addition to tap water of a cathode retarder of corrosion – sodium hexametaphosphate or sodium sulfite, the wear of steel samples decreased 25-40%. It is characteristic that with the addition to the same water of an anode inhibitor – nitrite of sodium, the wear was increased 50%. The case of the acceleration of the process of grinding of steel with the application of anode polarization is also described in work [32].

In the USSR to decrease the hydrogen sulfide corrosion of underground equipment of oil wells, a cheap and abundant inhibitor – formaldehyde, has found certain application. Combining with hydrogen sulfide, the formaldehyde will form a white insoluble substance, which is adsorbed on steel surfaces and retards the process of corrosion.

Satisfactory results were also obtained during industrial tests of another inhibitor of hydrogen sulfide corrosion – UFE-8, which is a product of the condensation of one mole technical phenol with eight moles of ethylene oxide. With the introduction of this inhibitor into the well from a calculation of 100-200 mgf per liter of obtained water, the speed of the hydrogen sulfide corrosion decreased 80% [27].

However, the field of application of the indicated inhibitors is limited by wells, the production of which contains hydrogen sulfide, i.e., a comparatively small number of wells. In a very large number of wells, where very intense corrosion-mechanical wear of the pipes occurs in spite of the absence of hydrogen sulfide,

the application of these inhibitors is deprived of meaning. An attempt by the authors to decrease the wear of the pipes in this category of wells by means of pumping formaldehyde into their pipe space did not give positive results.

Therefore, one should consider very important the search of inhibitors capable of decreasing the electrochemical corrosion of the equipment in wells whose production does not contain hydrogen sulfide.

Industrial tests of a water-soluble corrosion inhibitor, Katapone, for decreasing the wear of underground equipment of deep-pump wells were conducted by O. K. Arakelova and colleagues in 1964 in two wells watered 97% of the oil field administration "Ordzhonikidzeneft'" of the amalgamation "Azneft'."

The intense wear of the pipes and frequent breaks in rods in wheel No. 7298 were caused by the large content of hydrogen sulfide in its production. The small period of service of the underground equipment in well No. 1432, where hydrogen sulfide almost was absent, can be explained by the strong mineralization of the stratified water.

The inhibitor was measured out from a calculation of 0.1 kgf per 1 m^3 of obtained water. In well No. 7298 the solution of the inhibitor was fed continuously for one year and in well No. 1432 – for 6 months.

In well No. 7298, 6 months after the descent of a new set of pipes with pumping of the inhibitor a total of two cases of nonhermeticity, which earlier were observed considerably more frequently was noted. In well No. 1432 the number of underground repairs connected with the nonhermeticity of the pipes decreased by 86%.

It is especially necessary to stress that results obtained in well No. 1432 are of great interest, since it is typical for the category of wells in which the corrosion-mechanical wear of pipes is not connected with the presence of hydrogen sulfide.

From the point of view of the application of cheap and quite effective corrosion inhibitors, the experiment of A. P. Gasanov, who used calcium salt of acid Hydrone SB-3 to decrease the wear of the plunger pair of the deep-well pump (Fig. 48) [9] deserves attention.

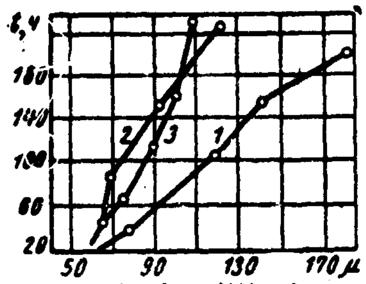


Fig. 48. Dependence of the wear of the plunger pair of the deep-well pump (after A. P. Gasanov [9]): 1 – without addition of the inhibitor; 2 – after addition of Katapone; 3 – after addition of calcium salt of acid Hydrone SB-3.

It is necessary to note that the application of oil-soluble corrosion inhibitors in oil wells is more rational, since they are apportioned proceeding from the quantity of obtained oil. Therefore, the required quantity of these inhibitors for treatment of the equipment of highly watered wells will be tens of times less than the necessary quantity of water-soluble inhibitors.

Long-term directions in the field of application of corrosion inhibitors for treatment of the equipment of oil wells are represented by treatment by inhibitors of the end-face zone and also the location on the end face of the well or under deep-well pump of solid inhibitors gradually dissolved in the obtained liquid.

Thus, experiments conducted in laboratory and industrial conditions, and also the available source material lead to the following basic conclusions concerning the effectiveness of different means of decreasing the corrosion-mechanical wear of steel parts:

1. The resistance to wear of steel with friction in corrosive liquids depends to a greater degree on its corrosion stability rather than on mechanical characteristics.

2. In the operation of machine parts, cases can be observed when even such corrosion-stable materials as stainless steels wear out intensely with friction in corrosive liquid media. Therefore the most radical means of preventing the corrosion-mechanical wear of steel at present is by eliminating or considerable weakening the effect of electrochemical corrosion on the process of wear with the help of electrochemical protection or corrosion inhibitors.

3. With friction in solutions of neutral salts and small values of specific pressure, the protection with the help of the concentrated protector masses can reduce the magnitude of wear of steel by approximately one order at the place of the protector installation. The effectiveness of the protector sharply decreases with removal from the place of its installation. Therefore, at very large dimensions of rubbing surfaces there is the rational application of dispersed protectors.

4. Good results can be attained with the help of corrosion inhibitors.

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13. ABSTRACT

The book gives an account of problems of the wear of constructional steel with friction in corrosive fluids and mainly in neutral salt solutions. The mechanism of mutual corrosion-mechanical wear of plain carbon steel and the effect of different factors on the intensity of this process are described. Results are given of laboratory and industrial experiments, which allow estimating the effectiveness of different means of decreasing the wear of steel articles with friction in solutions of neutral salts. The book is intended for engineering and technical workers of the chemical and petroleum industries; it can be useful for people engaged in the investigation of problems of corrosion-mechanical wear of metals. Orig. art. has: 48 figures and 11 tables. [AM9033182]

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Corrosion Inhibitors						

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